MUON ACCELERATOR R&D PROGRAM
A PROPOSAL FOR THE NEXT 5 YEARS

Draft 0.95

(August 18, 2008)

We request support to continue Muon Accelerator R&D at an enhanced level, sufficient to enable us to deliver, by 2013, the following:

1. A Zeroth-order Design Report (ZDR) for a multi-TeV Muon Collider, which will be based on (*a*) a physics and detector study that establishes the required performance and documents the associated physics reach, and (*b*) an end-to-end simulation of the Muon Collider accelerator complex based on demonstrated technologies or technologies that we anticipate can be demonstrated after a specified R&D program. The ZDR will also deliver the first defensible cost estimate, and identify areas of further technology R&D that should be pursued to improve the performance and/or the cost effectiveness of the design.

2. Participation in the International Neutrino Factory Design Study (IDS-NF) which aspires to produce a Reference Design Report (RDR) for a Neutrino Factory by 2012. The emphasis of the proposed U.S. participation is on (*a*) studying how the evolving Fermilab proton source can be used for the Neutrino Factory RDR design, (*b*) studying how the resulting Neutrino Factory would fit on the Fermilab site, and (*c*) the design, simulation and cost estimates for those parts of the Neutrino Factory front-end that are (or could be) in common with a Muon Collider.

3. Component development and experiments that are needed to inform the Muon Collider ZDR studies, and enable a down-selection of candidate technologies for the required ionization cooling channel and acceleration system.

Our proposed goals are motivated by the realization that in a few years the particle physics community will need information on which to base long-term decisions. If LHC results motivate a lepton collider beyond the energy scale of the ILC, then there are two possible options: a Muon Collider or CLIC. We anticipate that there will be a CLIC CDR in a 2010–11 timeframe, and a TDR in 2014–15. We believe that, with adequate support, we can deliver an equivalent Muon Collider ZDR that will enable the community to make an informed choice about its long-term future. In addition, there is significant overlap between Neutrino Factory and Muon Collider front-end designs. Participation in the IDS-NF studies can therefore benefit both Neutrino Factory and Muon Collider development, enable staging possibilities (from Neutrino Factory to Muon Collider) to be better understood, and prepare the way for a Neutrino Factory option at Fermilab if, for example, the unknown mixing angle θ_{13} turns out to be too small for experiments using more conventional neutrino beams.

The proposed program addresses one of the recommendations of the Particle Physics Project Prioritization Panel (P5), which was reconstituted by the High Energy Physics

Advisory Panel (HEPAP) at the request of the Office of High Energy Physics of the Department of Energy and the National Science Foundation in May 2008, namely,
"…The panel … recommends R&D for alternative accelerator technologies, to permit an informed choice when the lepton collider energy is established."[1]

Based on the recommendations of the Muon Technical Advisory Committee at its April 2008 review, the Muon Collaboration Oversight Group urged the U.S. Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Fermilab Muon Collider Task Force (MCTF) to create a plan for this 5-year R&D program. The main program elements of that plan are presented in Fig.1.

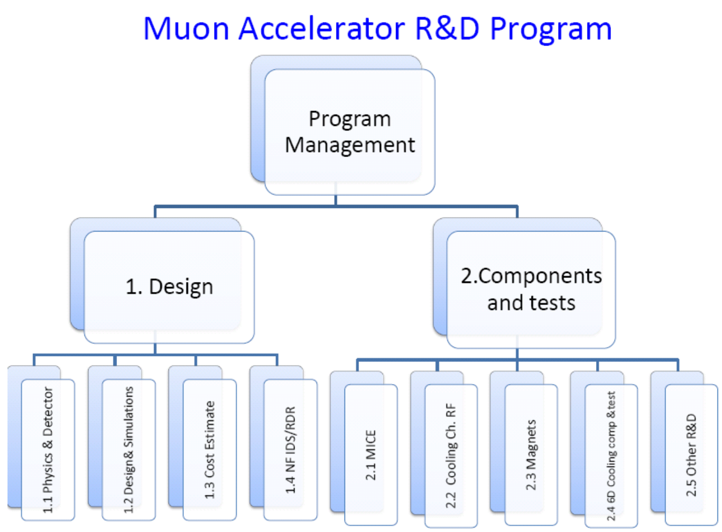

Fig. 1: Elements of the proposed Muon Accelerator R&D Program.

Organizationally, the program is foreseen to comprise participants of the five U.S. laboratories (ANL, BNL, FNAL, LBNL, and SLAC) and a number of U.S. universities and SBIR companies. Significant international collaboration with the UK and with other countries to understand, develop, and exploit the accelerator science and technology of muon accelerators is also anticipated. A possible organization of the R&D program management and oversight structure is shown in Fig. 2. The timing for a transition from the NFMCC and MCTF programs to a more formal structure such as this is not yet determined. Among other things, it will depend on our success in getting the proposed R&D program funded at an appropriate level.

In the structure shown in Fig. 2, the U.S. Muon Accelerator R&D Program Leader would provide technical and programmatic leadership, coordination and management of the U.S. MARP, and would be responsible to the Fermilab Director (representing the directors of the collaborating laboratories) for ensuring the successful execution of all elements of the program and for ensuring that the program goals are met. The Program Leader would represent the program in its interactions with DOE, with the management of the collaborating institutions, and with other organizations. He or she would be in

[1] See http://www.science.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf

constant communication with both the Office of High Energy Physics and with the Fermilab directorate on matters pertaining to financial and policy issues.

Communication with the directorates of the domestic laboratories is provided through the Laboratory Oversight Group. The status of the program would be reported periodically to the Laboratory Oversight Group. Independent technical review and advice could be provided on an *ad hoc* basis by a Program Advisory Committee, which would meet in person to hear presentations from the program participants and evaluate the quality and quantity of the work for the Fermilab Director.

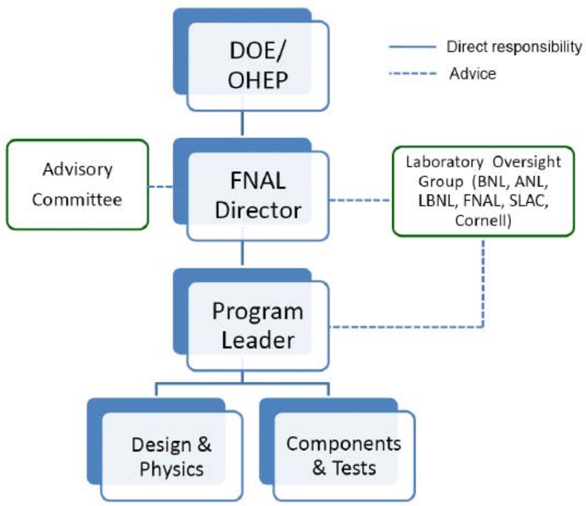

Fig. 2: Possible organization of the Muon Accelerator R&D Program.

The Muon Accelerator R&D Plan document is organized as follows:

1. INTRODUCTION

The physics potential of a high-energy lepton collider has captured the imagination of the world high energy physics community. Understanding the mechanism behind mass generation and electroweak symmetry breaking, searching for and perhaps discovering supersymmetric particles and confirming their supersymmetric nature, and hunting for signs of extra space-time dimensions and quantum gravity, constitute some of the major physics goals of a new lepton collider. In addition, making precision measurements of standard model processes will open windows on physics at energy scales beyond our direct reach. The unexpected is our fondest hope. The Muon Collider provides a possible approach to a multi-TeV lepton collider, and hence a way to explore new territory beyond the reach of present colliders. In addition, the Neutrino Factory has been shown to deliver unparalleled performance in studying neutrino mixing and has tremendous sensitivity to new physics in the neutrino sector.

We request support to continue Muon Accelerator R&D at an enhanced level, sufficient to enable us to deliver, within a few years, (*a*) a Muon Collider Zeroth-Order Design report (MC-ZDR), (*b*) a NF Reference Design Report (NF-RDR), and (*c*) results from component development and proof-of-principle demonstrations sufficient to inform the design choices associated with the MC-ZDR and NF-RDR studies. The present muon accelerator R&D funding is summarized in Appendix 1. The M&S and SWF support needed to conduct our proposed R&D program are summarized in Appendices 3 and 4, respectively, and the associated funding profile is presented in Appendix 5.

Muon Collider [1-4] and Neutrino Factory [5-11] accelerator complexes are shown schematically in Fig. 3. At the front-end both NFs and MCs require similar, perhaps identical, intense muon sources, and hence there is significant overlap in NF and MC R&D. The muon source is designed to deliver $O(10^{21})$ low energy muons per year within the acceptance of an accelerator, and consists of (*i*) a multi-MW proton source delivering a multi-GeV proton beam onto a pion production target, (*ii*) a high-field target solenoid that radially confines the secondary charged pions, (*iii*) a long solenoidal channel in which the pions decay to produce positive and negative muons, (*iv*) a system of rf cavities that capture the muons in bunches and reduce their energy spread (phase rotation), and (*v*) a muon ionization cooling channel that reduces the transverse phase space occupied by the beam by a factor of a few in each transverse direction. At this point the beam will fit within the acceptance of an accelerator for a NF. However, to obtain sufficient luminosity, a MC requires further muon cooling. In particular, the 6D phase-space must be reduced by $O(10^6)$, which requires a longer and more ambitious cooling channel. Finally, in both NF and MC schemes, after the cooling channel the muons are accelerated to the desired energy and injected into a storage ring. In a NF the ring has long straight sections in which the neutrino beam is formed by the decaying muons. In a MC, positive and negative muons are injected in opposite directions and collide for about 1000 turns before the muons decay.

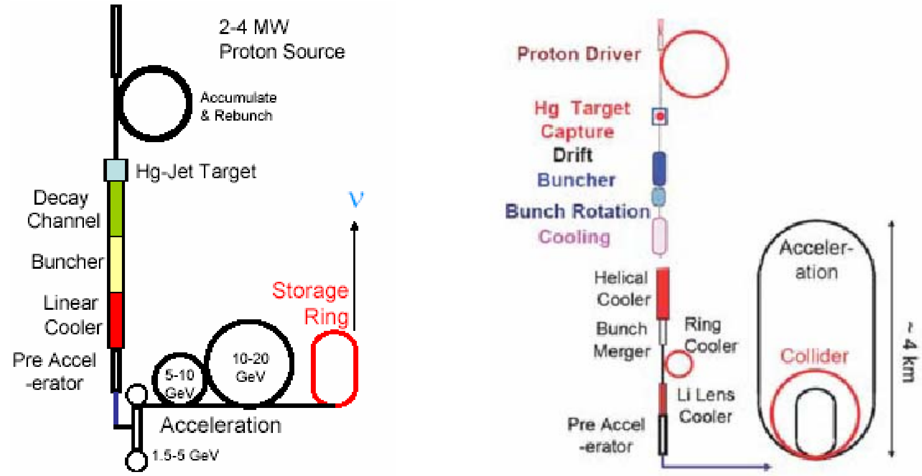

Fig. 3. (left) Schematic of 20 GeV NF; (right) schematic of 1.5 TeV MC.

The Neutrino Factory and Muon Collider Collaboration (NFMCC [12]) has been pursuing muon accelerator R&D since 1996. The initial work on the overall Muon Collider (MC) concept resulted in the "Muon Collider Feasibility Study Report" in June 1996 [3]. The Neutrino Factory (NF) concept emerged in 1997 [5]. Since 1997 the NFMCC has pursued both NF and MC design and simulation studies [4,6,9,10], together with component development and proof-of-principle demonstration experiments. In late 2006, the Muon Collider R&D effort was complemented by the addition of the Muon Collider Task Force (MCTF [13]) centered at Fermilab, but including participation from some NFMCC institutions and from the SBIR funded company Muons, Inc. [14]. The MCTF produced an initial R&D plan [15] in 2006, and a report [16] summarizing the first year of activities in January 2008. The focus of the MCTF studies has been on exploring designs and technologies for the 6D muon cooling channel needed (beyond the NF front-end) for a MC, and the design of the MC ring.

The NFMCC and MCTF programs are coordinated by the Muon Collider Coordinating Committee, which comprises of the leadership of the two groups. The muon accelerator R&D programs (NFMCC and MCTF) are reviewed annually by the Muon Technical Advisory Committee (MUTAC), which reports to the Muon Collaboration Oversight Group (MCOG), comprising of members from the directorates of the three NFMCC sponsoring laboratories (BNL, FNAL, and LBNL). Following the review this year, and given the present status of the R&D, both MUTAC and MCOG have encouraged [17] the NFMCC and MCTF to produce a joint 5-year plan aimed at delivering a Muon Collider ZDR by 2012, together with an appropriate contribution to the IDS-NF effort to produce an RDR.

This recommendation echoes the HEPAP P5 report (May 2008) *: "…besides ILC, other lepton collider options with the potential for greater energy reach and reduced cost need to be developed. ..Additional R&D is also needed on longer-term concepts including the muon collider and laser- and plasma-based linear colliders. Each has potential for greater energy reach and significant cost savings, but all still require feasibility demonstrations…*

Recommendations :
The panel recommends a broad strategic program in accelerator R&D, including work on ILC technologies, superconducting rf, high-gradient normal-conducting accelerators, neutrino factories and muon colliders, plasma and laser acceleration, and other enabling technologies, along with support of basic accelerator science."

The Report also emphasizes that : "*...a muon collider may be an effective means to reach multi-TeV energies. A muon collider would be free of the beam effects that can limit an* e^+e^- *collider at very high energies and would have the potential for highly efficient conversion of site power to useful collision energy. Using muons instead of electrons also has the advantage that recirculating linacs could use the accelerating structures multiple times to provide energy to both particle beams simultaneously. The challenge for a muon collider is to produce, collect, cool and accelerate enough muons to provide the luminosity required to study new phenomena in detail. Recent studies using a jet of mercury in a strong magnetic field have demonstrated that such a target is capable of surviving a four-megawatt proton beam. This first step toward providing muons is very encouraging. The next step is the demonstration of cooling using a combination of ionization energy loss and dispersion in a low-energy, low-frequency, acceleration system. Support for R&D for this program has been very limited. Demonstrating its feasibility or understanding its limitations will require a higher level of support."*

2. PRESENT STATUS

We believe that NF R&D is now ready for an international effort to produce an RDR by 2012, and MC R&D is ready for a concerted effort to produce a ZDR on a similar timescale.

The Neutrino Factory design studies that have prepared the way for an RDR include (*i*) Feasibility Study 1 [6,7] which was hosted by FNAL in 1999 and resulted in an end-to-end design and simulation for a NF together with a first cost estimate, (*ii*) Feasibility Study 2 [9], which was hosted by BNL in 2001 and resulted in an improved design that increased the performance of the NF to meet the requirements established by the corresponding physics studies [9], (*iii*) Feasibility Study 2a [10, 11], which, based on work in the period 2002–2005, updated the Study 2 design to improve its cost effectiveness, reducing the estimated cost by about one-third while improving performance, (*iv*) the International Scoping Study (ISS) [18,19,20], which was an international NF study hosted by RAL in 2006 that established a baseline design (that is similar to the Study 2a design). Following the internationalization of NF R&D and the successful outcome of the ISS, the International Design Study of a Neutrino Factory (IDS-NF) is now under way. Participants of the IDS-NF [21] aspire to deliver a NF RDR by 2012.

In addition to the design and simulation studies, the NFMCC has pursued component development and proof-of-principle experiments that inform the design studies and establish the viability of the proposed accelerator sub-systems. Studies 1 and 2 identified the systems requiring critical hardware R&D as:

1. a target that can be operated within a high field solenoid with a 4 MW primary proton beam, and
2. an ionization cooling channel in which rf cavities operate along with energy absorbers within a lattice of multi-Tesla solenoids.

The proof-of-principle MERcury Intense Target (MERIT) experiment [22], designed and constructed by the NFMCC with its international partners, ran successfully at CERN at the end of 2007. MERIT has established the viability of using a liquid-mercury jet injected into a high field solenoid with a 4 MW proton beam suitable for a NF and/or MC. The Muon Ionization Cooling Experiment (MICE) [23] is an international multi-phase proof-of-principle experiment that is hosted by RAL. The MICE muon beam line is currently being commissioned, and the remaining components have been designed and are under construction, with the NFMCC contributing major pieces of the test channel and instrumentation. MICE is expected to be completed by 2011–2012.

Complementing the MICE cooling channel demonstration, the MuCool program has been developing and testing cooling channel components. In particular, a good understanding of the performance of rf cavities operating within multi-Tesla solenoidal fields is critical if we are to have confidence in the design of muon ionization cooling channels. MuCool measurements [24] have shown that normal conducting rf (NCRF) copper vacuum cavities break down at lower gradients in multi-Tesla magnetic fields. The measurements also indicate that surface preparation is important, and that, although not yet tested with beam, the breakdown effect may be mitigated by using high-pressure gas within the cavity. In addition, new ideas for "magnetically insulating" the cavities and for using advanced surface treatments (i.e., atomic layer deposition, ALD) are promising. An important part of our proposed muon accelerator R&D plan is to vigorously pursue the rf R&D program to establish the viable options for high-gradient NCRF operating within magnetic lattices, and to measure the associated operational parameters.

MCTF and NFMCC researchers have made great progress in the design and simulation of a multi-TeV MC:

- a novel Interaction Region (IR) optics scheme has been proposed that allows significantly larger energy spread in the colliding beams than previously considered;
- muon beam dynamics in ILC-type 1.3GHz superconducting rf cavities was numerically studied;
- detailed modeling and particle tracking have been initiated for the three most promising ionization cooling channel approaches—the Helical Cooling Channel (HCC), the "Guggenheim" channel, and the "FOFO Snake" channel composed of tilted superconducting solenoids.

A significant program has been started to explore the upgrade parameters of the Fermilab 8 GeV "Project-X" linac, which is an appropriate candidate for a high-intensity proton source for the MC and/or NF complex. Altogether, this progress has led to a widely-accepted vision of Fermilab's long-term future in which the Muon Collider becomes the next U.S.-based energy frontier facility. In addition, the MCTF group has designed and installed a 400 MeV proton beam line from the FNAL linac to the MuCool Test Area (MTA). That beam line, which is currently being installed, will enable a series of new experiments with high intensity beams in the MTA hall.

Anticipating success of the MICE and NCRF R&D programs, by 2012 the proof-of-principle tests for a NF front-end will be complete. In parallel, we propose to pursue the basic hardware R&D needed to inform the technical choices that must be made in designing a MC 6D cooling channel. This, together with a vigorous design and simulation activity, will enable a MC ZDR along with a first cost estimate. Hence, with proper funding support, by the end of 2012 we would have both a NF RDR and a MC ZDR.

3. MUON COLLIDER ZDR PLAN

3.1 Physics and Detector Studies

In the next decade the physics of the Terascale will be explored at the LHC. Furthermore, planned experiments studying neutrino oscillations, quark/lepton flavor physics, and rare processes may also provide insight into new physics at the Terascale and beyond. This new physics might be new gauge bosons, additional fermion generations or fundamental scalars. It might be SUSY or new dynamics or even extra dimensions. In any case, it is hard to imagine a scenario in which a multi-TeV lepton collider would not be required to fully exploit the new physics.

A multi-TeV muon collider provides a very attractive possibility for studying the details of Terascale physics after the initial running of the LHC. The goal of our proposed physics and detector studies is to understand the required muon collider parameters (in particular luminosity and energy) and map out, as a function of these parameters, the associated physics potential. The physics studies will set benchmarks for various new physics scenarios (e.g., SUSY, Extra Dimensions, New Strong Dynamics) as well as Standard Model processes. The development of the physics case will be coordinated with the studies of detector performance, the design of the interaction region, and studies of the background environment. This coordination will be required to determine the signal efficiencies and background rates.

During the first two years we will set the physics case and establish the physics reach as a function of energy and luminosity of the collider. This will enable us to define the baseline parameters for the collider before the final year of ZDR design studies. It is important to establish a software platform for the physics studies as early as possible and dedicated resources, both manpower and equipment, are needed. The physics case needs to have broad laboratory theory group involvement and support. The larger theory community also needs to be included in this effort. A series of workshops will be held to stimulate interest and ideas from the larger theory community. An initial report on the physics case should be completed in this period.

The last two years will be devoted to detailed physics studies, including a more complete detector simulation. In this period detailed comparisons with other possible facilities, e.g., CLIC and SLHC, will be made. Any new information from LHC experiments on the physics at the Terascale will be incorporated and the physics case updated.

The detectors that will record and measure the charged and neutral particles produced in collisions at a Muon Collider are quite challenging. They must operate in an environment that is very different from the ILC or CLIC. Compared with hadronic interactions, lepton collisions generate events essentially free from backgrounds from underlying events and multiple interactions. They provide accurate knowledge of the center-of-mass energy, initial state helicity and charge, and produce all particle species democratically. Muon Collider detectors need not contend with extreme data rates. Most likely they can, in fact, record events without the need for electronic pre-selection and without the biases such selection may introduce.

The challenges for the detectors lie in the area of precision, radiation hardness and background rejection due to the overwhelming background from muon decays. To define the physics reach of the detector, a realistic simulation is needed, one that includes beamstrahlung, background from muon decays in flight, and a realistic evaluation of the bunch structure of the beams with time stamping. This would allow for realistic pattern recognition and track fitting of charged tracks. We foresee that in the first year setting up the simulation will take most of the effort. The simulation studies will be further refined and tools will be developed in the subsequent years to establish the physics reach.

As for vertex detectors and trackers, there is sufficient overlap of the requirements for the LHC upgrade experiments and the ILC experiments that we do not see any additional effort needed for the ZDR for a Muon Collider detector. We do, however, see a significant effort in establishing the required calorimetry for a Muon Collider detector. To mitigate detector backgrounds, previous Muon Collider final focus shielding designs resulted in an uninstrumented cone in the forward direction of 20° opening angle. Possibilities for limiting the opening angle or partly instrumenting this cone need to be explored. Many of the interesting physics processes at a lepton collider appear in multi-jet final states, often accompanied by charged leptons or missing energy. The reconstruction of the invariant mass of two or more jets will provide an essential tool for identifying and distinguishing *W*s, *Z*s, *H*s, and top, and for discovering new states or decay modes. Ideally, the di-jet mass resolution should be comparable to the natural decay widths of the parent particles, around a few GeV or less. Improving the jet energy resolution to 3–4% of the total jet energy, which is about a factor of two better than that achieved at LEP, will provide such di-jet mass resolution. Achieving such resolution represents a considerable technical challenge. The main emphasis for ILC detectors is to employ "Particle Flow" to improve the jet energy resolution. It is unclear if this algorithm will retain this performance with jet energies increasing to 1 TeV and above. We anticipate that the majority of the detector R&D to be carried out is to establish the calorimetry for a Muon Collider detector operating in a high background environment. A promising technology is dual readout total absorption calorimetry, which we expect to explore.

Our detector study plan is:

Year 1: Establish a realistic simulation of the Muon Collider background environment, and study the final-focus shielding design.

Year 2: Define detector requirements based on physics studies and expected backgrounds, and hence identify and plan the detector R&D that will best inform the ZDR studies, and begin this R&D.

Years 3–4: Carry out detector R&D and further simulation studies, establishing the likely detector performance at the end of year 3 and writing the detector section of the ZDR in year 4.

3.2. Design and Simulation Overview

A major focus of NFMCC-MCTF activities is the design and simulation of the accelerator subsystems required by a multi-TeV muon collider. Here, we describe the accelerator design and simulation tasks that must be accomplished in order to complete a Muon Collider ZDR by 2012. The possibility of building a Muon Collider was first seriously considered by Budker, Skrinsky and their colleagues at Novosibirsk around 1970 [25]. Practical methods for implementing such a collider were studied by the U.S. Muon Collaboration[2] in the late 1990s [3,4]. The recent burst of activity in collider design studies was spurred by the creation of the MCTF at Fermilab in 2006 [26].

At the current time there are three overall scenarios for the MC accelerator systems that are under active investigation. These scenarios involve different choices for the desired collider parameters and for the design of the accelerator subsystems. These scenarios have come to be identified by their requirements for the transverse emittance in the collider ring as the low (LEMC), medium (MEMC), and high (HEMC) emittance muon colliders. Main parameters for these scenarios are listed below in Table 1.

Table 1. Parameters for a 1.5 TeV (c.m.) muon collider [26].

	LEMC	MEMC	HEMC
Avg. luminosity (10^{34} cm^{-2} s^{-1})	2.7	1.33	1
Avg. bending field (T)	10	6	6
Proton driver repetition rate (Hz)	65	40	13
β^* (cm)	0.5	1	1
Muons per bunch (10^{11})	1	11.3	20
Norm. Transv. Emittance (μm)	2.1	12.3	25
Norm. Long. Emittance (m)	0.35	0.14	0.07
Energy spread (%)	1	0.2	0.1
Estimated muon survival (%)	31	20	7

[2] This is the original name for what later became the NFMCC.

There are a number of reasons why several alternative designs are being considered. Muons have well-known features that greatly complicate the accelerator design. Foremost among these are the short lifetime and the fact that they are diffusely produced in pion decay. As a result, muon beams are generated with emittances and energy spreads that are enormous by conventional accelerator standards. Some of the differences in the collider scenarios reflect different philosophies about the optimal choice of collider parameters, for example the number of muons per bunch or the pulse repetition rate. An important goal of the R&D program outlined here is to characterize both the performance and cost of the various alternatives in order to select the most promising one for further exploration and optimization.

A crucial aspect of a Muon Collider is the massive use of ionization cooling, a technique that has never been used before in an accelerator design. There is a lot of debate on the optimal design of these cooling channels and on the technical feasibility of the magnets and rf cavities that must be used to reduce the muon emittance to the required levels. The feasibility of these channels is uncertain at the present time because they depend on experimental questions that have not yet been answered. The two most important examples are the limit on the gradient of normal-conducting rf cavities in strong magnetic fields, and the possible breakdown of gas-filled rf cavities by intense muon beams.

3.3 Goals

As already noted, one of the major goals of the current R&D program is to select among the accelerator alternatives and decide on a single baseline collider design by 2011. To accomplish this, we anticipate the following steps:

(*i*) Develop an end-to-end design for a multi-TeV MC that is based on demonstrated technologies and/or technologies that can be demonstrated after a specified R&D program. Identify and document the key R&D tasks.

(*ii*) By means of end-to-end simulations (including beam-beam simulations to give luminosity estimates), demonstrate that the design will meet the required machine performance parameters. The sub-systems simulated will be based on sufficient engineering input to ensure that the assumed design includes a reasonable level of realism (i.e., realistic gradients, magnetic fields, alignment tolerances, safety windows, spatial constraints, etc.). Simulations will cover proton driver, target, and all downstream systems up to and including the collider ring; beam transfers between systems will be included as part of the simulation.

(*iii*) Document the baseline machine design, including required technologies, description of subsystems, performance estimates (luminosity, cooling performance, backgrounds), and fabrication and installation approaches (sufficient for costing purposes).

3.4 Schedule

2008–2010	Study proposed alternatives for the accelerator subsystems. Simulate subsystem performance using defensible parameters. Cross-check promising subsystems with two simulation codes.
2011	Specify a baseline accelerator design and focus on optimizing it, minimizing work on non-baseline alternatives. Simulate representative matching sections. Carry out representative tolerance studies. Freeze accelerator design.
2012	Complete the design of all matching sections. Do an end-to-end simulation of the accelerator systems. Do detailed tolerance studies. Do necessary simulations for the collider ZDR.

The estimated amount of effort involved in these tasks will be described in Appendix 4 and is summarized in Section 9.

3.5 Proton Driver Design Activities

If MC and NF facilities are separately designed and optimized, the front ends tend to diverge somewhat because the MC needs luminosity whereas the NF needs flux. Nevertheless, there is considerable overlap between the proton beam power needs of an energy-frontier MC and those of a NF. In many ways, the MC is somewhat more demanding on its front end than is the NF, so any facility that meets the beam-power needs of the former is likely to meet the needs of the latter.

Several muon collider design efforts have generated parameter sets that call for proton beam powers of several megawatts. The most common requests fall in the neighborhood of 3–4 MW. At this stage, most designs are optimistic and none have been fully vetted, so it is advisable to provide considerable performance contingency. The required proton beam power is not likely to be a strong function of the center-of-mass energy of the collider.

Our vision for the proton driver is to base its design on the Project X linac being proposed for Fermilab. We assume that a reference design for the baseline version of Project X will be prepared independently of our effort. Thus, we consider here only the additional effort needed to determine the specific modifications to accommodate the requirements of a Muon Collider.

3.5.1 *Proton bunch structure rings*

To prepare the proton beam suitably for our purposes, we must modify its bunch structure compared with the specifications for Project X [27]. In particular, for a MC the preferred bunch length is in the range of 1–3 ns at a repetition rate in the range of 10–60 Hz. The required accumulator and bunch compression rings will be studied in three ways:

- developing conceptual designs
- performing evaluations of instabilities (analytic and/or simulation)
- carrying out tracking studies including realistic errors

3.5.2 *Power upgrade to 4 MW*

The MC requirements call for a proton beam power up to about 4 MW. The intensity capability of Project X must be enhanced to achieve this beam power. Aiming for power levels even beyond the 4-MW level would seem prudent, as discussed above. Studies will be carried out by:

- developing conceptual designs
- performing evaluations of instabilities (analytic and/or simulation)
- carrying out tracking studies including realistic errors

3.5.3 *CW mode linac*

Because the proposed MC repetition rate is high, it is worthwhile to consider the technical implications of implementing the Project X linac as a CW device. Once again, the approach would involve:

- developing conceptual designs
- performing evaluations of instabilities (analytic and/or simulation)
- carrying out tracking studies including realistic errors

3.6 Target Design Activities

Much of the design work for the target facility was done as part of the Study 1 [6] and Study 2 [9] reports for a Neutrino Factory and remains valid. However, there is still work needed to flesh out the details of the target system. There are two aspects to this work, the first related to gaining enhanced understanding of the MERIT experiment [28] and the physics issues associated with the Hg-jet target, and the second related to the facility design issues.

3.6.1 *Simulations*

In the next few years we will need to continue benchmarking the results of the MERIT experiment against detailed simulations of what was expected. Understanding the production rates, the disruption of the jet, and the magnetic field effects will be the key areas of concentration. This work will also need to be extended to the configuration anticipated for an actual NF or MC, which differs somewhat from the setup used in MERIT for logistical reasons. Studies of nozzle performance will be carried out. These will involve both simulation and experimental work to optimize the nozzle geometry and to study its operational longevity.

One aspect of the target system not covered in the MERIT experiment is that of interaction of the Hg jet and/or the proton beam with the Hg pool that serves as the beam dump. Evaluation of schemes to distill the mercury to reduce its radiation levels must be defined and their efficacy evaluated.

3.6.2 *Facility design*

There are also aspects of the facility design that bear further examination. These include assessment of designs for the upstream and downstream containment windows through which the beam must pass, defining a workable remote-handling or robotics scheme for changing components in this highly radioactive area, and design of the water-cooled tungsten carbide inner shielding area. Based on the concepts being developed for other parts of the facility, it will be worthwhile (see Section 5.3.4) to examine the possibility of utilizing HTS conductor for some portion of the hybrid target solenoid. The HTS material tends to be very radiation resistant—a potential advantage in the target environment. This study would be done in concert with other HTS studies of interest to the MC.

3.7 Front End Design Activities

Much of the current effort on the collider design is devoted to the "front end" subsystems. In all cases, the front end starts with a pion decay channel and a phase rotation channel to reduce the energy spread of the muon beam. Most of the rest of the front end comprises ionization cooling channels to reduce the emittance of the muon beam. The cooling starts with a pre-cooler to reduce the transverse emittance. Positive and negative muons are then separated and sent through dispersive 6D cooling lattices to simultaneously reduce the transverse and longitudinal emittances.

The three collider scenarios we are presently investigating differ mainly in the details of how the cooling is carried out. The HEMC scenario uses a large-pitch helical channel known as the "Guggenheim" to do the 6D cooling. After sufficient longitudinal cooling, the beams are recombined and sent through a final cooling channel containing 50-T HTS solenoids that reduces the normalized transverse emittance to the level required by the collider. The LEMC scenario emphasizes additional cooling and a reduced number of muons per bunch. It uses a tighter-pitch helical cooling channel for 6D cooling and Parametric Ionization Cooling (PIC) and Reverse Emittance Exchange (REMEX) for the final cooling. The muon bunch trains are recombined at higher energy. The MEMC scenario uses parts of each of the previous two scenarios together with a new idea for 6D cooling in a wiggler-like channel called the "FOFO-snake."

3.7.1 *Decay, bunching, and phase rotation*

The first section of the front end captures the pions produced at the target, allows them to decay into muons, bunches the muon beam and reduces its energy spread. Two new alternatives need to be compared with Study 2a—the Neuffer 12-bunch scheme and the LEMC approach. The former scheme is suitable either for a NF or a MC. However, to assess its performance and cost it must be studied under more realistic assumptions that correspond to a practical implementation. There are several steps needed for this:

- replace continuous magnetic fields with an actual coil geometry
- use "families" of rf cavity frequencies rather than continuously decreasing frequencies where all cavities are different
- include absorbers and rf windows in the simulation
- examine an alternative magnetic lattice having partially bucked fields to reduce the field on the rf cavities
- check the sensitivity to errors of the final configuration

3.7.2 *Pre-cooling*

A first stage of transverse cooling is useful before separating the muon charges and sending the muon beams into the 6D cooling channels. Two main alternatives are being studied as a possible replacement for the Study 2a cooling channel. These are

- a Study 2a channel with hydrogen gas absorbers in place of the LiH rf windows
- a LEMC configuration

Our SBIR partner, Muons, Inc., is studying an alternative pre-cooler design that uses liquid hydrogen and no rf in a momentum-dependent helical cooling channel.

Although the transverse emittance of the muon beam is very large after the capture and phase rotation sections, it may be possible to use quadrupole magnets for focusing in the first cooling channel. This will be studied briefly to see if it is feasible and if it offers any advantages over solenoidal focusing.

3.7.3 *6D cooling*

The bulk of the muon cooling is done in the 6D cooling channels. There are three main schemes for doing the 6D cooling for the collider. Additional subsystems for charge separation and charge recombination are required, and low-energy bunch merging may also be needed. The three schemes [29] include the Guggenheim channel, the helical cooling channel (HCC), and the FOFO-snake channel.

Guggenheim channel. The Guggenheim channel uses a large-pitch helical lattice. This approach has been under study for a number of years, but much remains to be done. Code must be developed and comparisons must be made between alternative ways of modeling the fields in ICOOL, either using 3D field maps or a multipole expansion. The benefits of a "tapered"[3] channel must be assessed. Matching sections must be designed and realistic parameters for absorbers and windows must be used in the simulations. Performance will be checked using both ICOOL and G4beamline. If magnetic shielding is needed between "turns" in the lattice, its effect must be evaluated. Also, an evaluation of a configuration with magnetically insulated cavities will be made. To make sure collective effects are benign, we will model space-charge effects at the end of the channel. Finally, an exploration of error sensitivity will be carried out.

Helical cooling channel (HCC). A tight-pitched helical cooling channel (HCC) made up of a series of solenoids with their centers arranged along a helical path is also under active investigation [30]. The implementation of such a channel with embedded rf cavities is challenging. A model incorporating realistic cavity parameters will be developed and tested via simulations. A model of the helical magnet must also be developed and its properties incorporated into the simulations. This work is already under way. Matching sections between the HCC and the rest of the front end need to be designed and simulated. Overall optimization of the entire system must be carried out. Here too, we will model space-charge effects at the end of the channel to make sure collective effects are benign, and we will explore error sensitivity. As this system is pressurized with H_2 gas, we will need a structural analysis of the isolation windows and a detailed safety analysis.

FOFO-snake channel. The FOFO-snake channel consists of a series of tilted, translated solenoids following a straight path [31]. It acts like a planar wiggler and has the great advantage that both muon charges can be cooled in the same channel. There are several possible implementations of this design to study, including a gas-filled cavity version, a vacuum cavity version, and a magnetically insulated version. The other activities required to assess this approach are the same as those for the other cooling channel options, namely, studies of matching sections, space-charge effects, and error sensitivity.

Charge separation and recombination. The helical cooling channels (HCC and Guggenheim) can only transmit muons of a given charge. In these scenarios the muons must first be separated and then recombined after the 6D cooling is finished. Various approaches, including dipole splitters and bent solenoid versions will be designed and compared. Error sensitivity will be examined.

Low-energy bunch merging. The HEMC scenario combines the muon bunch train produced in the decay and phase rotation section into the single bunch required by the collider in the center of the 6D cooling section. Various alternatives will be explored, including the use of planar wigglers and helical wigglers. A lattice based on magnetically insulated cavities will also be examined. All comparisons will consider error sensitivity.

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[3]By "tapering" we refer to changes in lattice parameters along the cooling section that cause the equilibrium emittance of the downstream portions to be reduced compared with the early part of the channel. This enables the beam emittance to always remain well above the equilibrium emittance—a condition that results in optimal cooling efficiency. Such an approach, used to advantage in Study 2, is only possible in a single-pass channel.

3.7.4 *Final cooling*

One of the most challenging goals in the collider design is to get a final normalized transverse emittance on the order of 2–25 μm. The strategy used in the cooling channel design is to end the 6D cooling section when the longitudinal emittance is well below the value needed by the collider. Then, either brute force transverse cooling or reverse emittance exchange can be used to obtain the required transverse emittance. Four alternatives are being considered for the final stage of cooling. Some schemes use an additional subsystem for high-energy bunch merging.

<u>50-T HTS channel</u>. The 50-T channel uses a straight lattice of very high field HTS solenoids to do the final cooling [32]. Development of this channel requires an optimization of the lattice parameters for various assumed maximum values of the solenoid strength. Lattices must also be matched on both ends and these sections need to be designed and simulated. Collective effects, especially space charge, will be examined, as will magnetically insulated cavities. The selected design will be subjected to an error sensitivity study to validate its performance.

<u>PIC-REMEX</u>. Muons Inc. is studying the use of parametric resonance together with ionization cooling in a solenoid lattice to produce a very low emittance beam [33]. This scheme also incorporates a final stage of reverse emittance exchange [34]. Several different lattices for PIC (Parametric Ionization Cooling) and REMEX (Reverse Emittance Exchange) will be developed and studied, including aberration-corrected versions and magnetically insulated versions. In each case, matching sections will be designed and channel performance will be simulated, including space-charge effects and the effects of errors.

<u>Low-beta bucked-coil lattice</u>. A third idea for final cooling uses a solenoid lattice operating in a parameter regime where the minimum of the beta function lies at the center of the focusing solenoids. This configuration can produce very small beta functions and naturally allows the addition of bucking coils to minimize the magnetic field present at the rf cavities. We will design and simulate cooling in a straight lattice, and investigate alternative designs that incorporate dispersion. We will also design the required matching sections, and look at space-charge effects and the effects of errors.

<u>Lithium lens channel</u>. The idea of using a lithium lens channel for the final cooling has been considered since the first MC designs. This is currently being studied by the UCLA group. A straight cooling lattice incorporating the lithium lenses must be designed and simulated. Designs for the necessary matching sections must be made. Space-charge effects and the effects of errors need to be investigated.

<u>High energy bunch merging</u>. In the LEMC scenario, all cooling is done on a muon bunch train. This train is accelerated to high energy before being combined to a single bunch. The bunch recombination ring must be designed and simulated [35]. Injection and extraction systems and transfer lines must be designed and simulated, as must the rf gymnastics to accomplish the bunch merging. The sensitivity to errors must be studied.

3.7.5 *End-to-end simulation*

One of the major goals for the MC ZDR is to do an end-to-end simulation of the whole front end of the collider. This will require that we join all the baseline subsystems into a single model in ICOOL. We will also make a single model of the whole channel using the G4beamline code. Then we will need to make high statistics runs through the full channel. The results from ICOOL and G4beamline will be compared and any discrepancies resolved. We will study the sensitivity of the results to the physics models used in the simulations. We will also study the sensitivity of the performance to the hardware parameters. We will study the muon polarization that is produced in the channel, since that may have an effect on the physics produced by the collider. We will also study the effects of space charge at critical locations using a dedicated space-charge code.

3.7.6 *Front end code development*

The codes ICOOL and G4beamline have been the major tools for designing the front end systems. We will continue to maintain and make minor improvements in these codes. More major changes in the codes will be made as necessary to investigate the performance of the subsystems discussed previously.

3.7.7 *RF system*

One of the major uncertainties in the front end design at the moment is the breakdown characteristics of the normal conducting rf cavities in a strong magnetic field, and the possibility of beam-induced breakdown of gas-filled rf cavities. There are plans for studying both of these subjects experimentally (see Section 5.2.1), although definitive results may not be available until the end of 2009. As a precaution, we are investigating a number of methods to interpret the experimental results and to ameliorate the problem if it does in fact occur. For understanding the experimental results we need to simulate beam breakdown in gas-filled cavities and develop a model of breakdown in vacuum cavities. Understanding breakdown may require detailed space-charge simulations. To ameliorate the possible effects, we are investigating:

- fully investigate the application of SCRF processing techniques to copper cavities
- using atomic layer deposition to prevent the cavity from breaking down
- designing bucked coil lattices that minimize magnetic fields on the cavities
- designing a magnetically insulated cavity where $\vec{B}$ is perpendicular to $\vec{E}$.

3.8 Acceleration Design Activities

After cooling, the muon acceleration systems must increase the muon kinetic energy from 140 MeV to, say, 750 GeV at the collider.

3.8.1 *Acceleration to high energy*

A choice must be made regarding the scenario for acceleration. We assume, as a starting point, a beam accelerated by some variant of the acceleration scenario for a NF, possibly with an additional stage or stages added. The power in the final muon beam is substantial, and thus the efficiency of the acceleration system is an important consideration. A decision must be made between a number of possible scenarios listed below.

Very rapid cycling synchrotrons. The advantage of a synchrotron for acceleration is that it allows a large number of passes through the rf cavities, reducing both the capital and operating costs of the machine. The challenge is that this acceleration approach requires rapid variation of the magnet fields [36]. While it may be possible to do this, a short ramping time requires magnets with very thin laminations to manage eddy currents. Such "synchrotron" designs are often a variant of a true synchrotron design, in the sense that the fields do not increase uniformly with momentum in order to keep a high average field. A mixture of fixed-field superconducting and ramped warm magnets has been suggested. It must be verified that the rapid changes in the conventional magnets do not induce quenches in the adjacent superconducting devices. It may be necessary to modify the way the magnets ramp to ensure that the beam remains synchronized with the rf. Studying this acceleration scenario will include:

- producing complete lattice designs that accelerate to the desired final energy
- performing engineering studies on the magnets to determine their feasibility and cost
- studying the requirements for the rf systems

RLA designs. A recirculating linear accelerator (RLA) is a straightforward option for accelerating to high energies [37]. Its primary disadvantage is the practical limitation on the number of passes the beam can make through the linac due to the complexity of the switchyard. The study of this acceleration scenario will involve:

- creating lattices that will accelerate to the final energy, including the spreader and recombiner sections
- studying the requirements for the rf systems

Alternative scenarios. Acceleration for a muon collider has had limited study up to this point. In addition to the two scenarios described above, a number of alternative scenarios could be considered. One is to combine the above two options, creating an RLA that uses fast-ramping magnets, allowing for a greater number of passes. Using FFAGs, as has been proposed for a NF, is another possibility. This choice is potentially advantageous, since FFAGs generally become more efficient at higher energy. Another choice is to incorporate a linac used in the proton driver into the muon acceleration chain. Simulation studies will be used to determine which alternatives have the potential to give the best performance. For purposes of comparison, we will produce designs for any interesting alternatives at a comparable level of detail to the other systems.

3.8.2 *Low energy acceleration*

The low-energy portion of the acceleration chain (up to 50–100 GeV) will likely be accomplished with techniques similar to those in a Neutrino Factory (and perhaps even using the systems from an existing NF). To design this portion of the MC facility we will

- study to what extent the NF acceleration system is suitable for the MC
- make any necessary modifications to the NF acceleration scenario
- include additional similar stages to the NF acceleration scenario where that would be advantageous

3.8.3 *Transfer line designs*

As for a Neutrino Factory, the MC acceleration system requires transfer lines between acceleration stages and between the final acceleration stage and the collider ring. These transfer lines will each be designed to optimize the phase-space distribution for injection into the next system in the chain.

3.8.4 *Single-particle simulations*

The beam must be tracked through the entire acceleration system, from cooling up to the collider ring. It is likely that some code development will be needed to achieve this.

3.8.5 *Collective effects*

Because the intensity of a coalesced bunch for the collider will be quite high, collective effects constitute a potential operational limitation. There are several such effects to consider, and these must be simulated to assess their impact on performance.

<u>Impedance-driven collective effects</u>. Although the muon beam spends only a short time in the accelerator complex, its individual bunches have a substantial charge, and impedance-driven collective effects are likely to be very important. For acceleration, the major contribution to the impedance will be the rf cavities. For the MC parameter regime, the charge in a single bunch is large enough to extract a substantial fraction of the stored energy from one of these cavities. As this is a nonstandard operating regime we must study its beam dynamics implications. We will study the effect of short-range wakes, probably the most important effect, as well as long-range wakes.[4] We will also consider the effects of having both signs of muons in the machine simultaneously.

<u>Parasitic collisions</u>. Most acceleration scenarios envisage having both muon signs in the same accelerator. The bunches will thus collide parasitically many times during acceleration. The large bunch charge means that the crossings could substantially perturb the beam, so the importance of this must be quantified.

[4]These will primarily concern fundamental-mode beam loading, but could be affected by cavity higher-order modes as well, so both aspects need investigation.

Two-stream instabilities. There is often a question of whether two-stream instabilities (electron cloud, fast-ion) are important in these machines. They are not expected to be so, due primarily to the large amount of time between bunch passages (since there are only a small number of bunches), but his must be verified.

3.9 Collider Ring Design Activities

The final part of the MC facility is the collider ring, where the muon beams collide at low-beta interaction points. The proper design of this ring is a prerequisite for the success of the whole project. The design of the interaction region is strongly tied to the design of the detector. Close collaboration between the two groups will be necessary to achieve an acceptable outcome. There are currently three ring designs under consideration. Two of the designs assume high normalized transverse emittance (~12–25 μm) in the collider [38]. They differ in the location of the closest dipole to the interaction point (IP) and the arrangement of the sextupole families. The other ring design, for the LEMC scenario, assumes a low normalized transverse emittance of 2 μm.

The goal of these studies is to develop a lattice design that provides:

- parameters necessary to achieve the design average luminosity (2×10^{34} cm^{-2} s^{-1} at 0.75+0.75 TeV), including
  - $\beta^* < 1$ cm in the case of 2 IPs
  - low momentum compaction, $|\alpha_c| < 1 \times 10^{-4}$, in order to obtain an rms bunch length below 1 cm (i.e., $\sigma_\ell < \beta^* < 1$ cm) with moderate rf voltage
  - small circumference $C \sim 3$ km (since luminosity scales as $1/C$)
- momentum acceptance (0.5–1%) and dynamic aperture sufficient to accommodate a muon beam with the emittance expected from a 6D ionization cooling channel
- reasonable tolerances on strength, field quality, and alignment errors
- stability of coherent motion of bunches containing $1–2 \times 10^{12}$ muons
- compatibility with the detector and with magnet protection from secondary particles

Work on collider lattices must go hand-in-hand with the magnet, superconducting rf, and detector studies. It includes the steps indicated below:

3.9.1 *Analysis of basic solutions*

We need to carry out basic lattice design studies of the interaction region (IR), taking into account the constraints due to quadrupole gradients and practical magnet apertures. We need to examine various chromatic correction schemes, such as special correction sections versus local correction within the IR. We need to study the trade-offs of using FODO cells versus achromats for the arcs. We will also examine the performance trade-offs of having one versus two IRs.

3.9.2 *Lattice composition and matching*

Complete ring lattices need to be designed including special matching sections, injection, collimation, and beam abort.

3.9.3 *Design of chromaticity and nonlinear detuning correction circuits*

The chromaticity needs to be studied in higher order and the design of the correction schemes needs to be optimized.

3.9.4 *Dynamic aperture*

The muon beams need to circulate in the collider ring for ~1000 turns. Tracking studies will be made taking into account the effects of magnet imperfections (strength, field quality, and alignment errors) and beam-beam interactions.

3.9.5 *Simulation of secondary particle fluxes and detector backgrounds*

Placing dipoles and quadrupoles near the IR has a significant effect on the backgrounds in the detector. Conversely, the design of the detector constrains the location and size of the IR magnets. In order to find a mutually acceptable solution, we will iterate on the IR and detector designs.

3.9.6 *RF system*

We need to do the design, analysis, and simulation of the rf system. We will optimize the design of the accelerating structure, including a higher-order-mode (HOM) analysis. We will then perform wakefield and impedance simulations to evaluate the requirements for HOM damping and/or feedback systems.

3.9.7 *Auxiliary systems*

We will develop detailed scenarios for closed-orbit correction and explore other tuning algorithms. We will design the injection system, the beam abort system and the collimation system.

3.9.8 *Coherent effects*

We need to calculate the impedance budget and do a stability analysis of the coherent motion of the muon beams.

3.10 SWF and M&S Requirements

The collider design and simulation effort is summarized in Table 2. Effort requirements (in person-months, p-m) were developed based on experience over recent years in what is

Table 2. Summary of SWF requirements for MC design and simulation effort.

System	Total required effort [p-m]	Current effort [FTE]	New effort needed [FTE-years[a)]]
Proton driver	240	0.5	21
Target	90	0.5	7
Front end	415	7.1	11
Acceleration	180	0.7	14
Collider ring	190	1.0	14

[a)]FTE-years refers to integrated effort. For example, 9 FTE-years could be 3 FTE effort for 3 years or 2.25 FTE effort for 4 years.

presently needed to carry out the design and simulation studies of the NFMCC and MCTF. The estimated number of people involved in this effort is summarized in full-time-equivalents (FTEs)[5].

We estimate that the present effort level for the MC work is approximately 10 FTEs. In evaluating the incremental effort level needed to complete the design and simulation work needed to prepare the MC ZDR, we assume that *all the people currently working on this activity will continue at the same level of effort through 2012*, contributing nearly 40 FTE-years to the total effort**.** In order to complete all the necessary studies by 2012 we estimate that ~67 FTE-years of effort will be required in addition to our current R&D activities.

3.11 Cost Estimation

One of the required tasks in preparing for the MC ZDR is to obtain a cost estimate for the facility. At the stage of development reached by 2012, it is expected that the cost estimate will use a “top-down” approach as opposed to the more rigorous “bottom-up” approach. As the first step in this process, a Work Breakdown Structure (WBS) must be set up. Table 3 shows a preliminary WBS scheme that will be used to begin the design and cost-estimating process.

To estimate the resources required to obtain the cost estimate we make several assumptions:

- The WBS will be organized by accelerator system, as indicated in Table 3
- The cost exercise will primarily occur in 2012, after the machine design is frozen
- There will 1–2 engineers “consulting” part time throughout the design effort

The estimated effort level is summarized in Table 4. The total effort required is approximately 8 FTE integrated over the period from 2009–2012.

[5]As is conventionally done, we assume a conversion factor of 1 FTE = 10.5 p-m, to account for holidays and vacations.

Table 3. Initial MC WBS scheme.

WBS	Title
1	**Muon Collider Accelerator Comple**
1.1	Proton Driver
1.1.1	Ion Source
1.1.2	Beam Transport
1.1.2.1	LEBT
1.1.2.2	MEBT
1.1.2.3	Linac to Target
1.1.3	Linac
1.1.3.1	Cryomodules
1.1.3.2	RF source
1.1.3.3	Instrumentation
1.2	Target Station
1.2.1	Hg jet system
1.2.2	Capture and Decay Channel
1.3	Front End
1.3.1	Bunching
1.3.2	Phase Rotation
1.3.3	Initial Cooling Section
1.3.4	6D Cooling Section
1.3.5	6D to 4D Matching Section
1.3.6	Final Transverse Cooling
1.3.7	Matching to Linac
1.4	Acceleration System
1.4.1	Linac
1.4.2	RLAs
1.4.3	Final Acceleration
1.4.4	Ring Injection Line
1.5	Collider Ring
1.5.1	Magnets
1.5.2	Vacuum
1.5.3	Instrumentation
1.6	RF Systems
1.6.1	NCRF
1.6.2	SCRF
1.6.3	Power Source
1.7	Control System
1.8	Conventional Facilities
1.8.1	Tunnels
1.8.2	Above-ground Support Buildings
1.9	Project Management

Table 4. Engineering effort in support of MC ZDR effort. Ongoing contributions will be involved in the project for 4 years; the remaining persons are assumed to participate only during 2012, after the accelerator design is frozen.

Specialty	FTE	Ongoing?	Total (FTE-yr)
Sr. Mech. Eng.	0.2	Y	0.8
Sr. Electr. Eng.	0.2	Y	0.8
Proj. Eng.	1.0	N	1.0
Vacuum Eng.	0.5	N	0.5
PS and Diagnostics Eng.	0.5	N	0.5
Plant Eng.	1.5	N	1.5
RF Eng.	1.0	N	1.0
Cryogenics Eng.	0.5	N	0.5
Controls Eng.	0.5	N	0.5
Magnet Eng.	0.5	N	0.5
Survey and Alignment Eng.	0.2	N	0.2
ES&H specialist	0.2	N	0.2
TOTAL			8.0

4. NEUTRINO FACTORY RDR PLAN

A Neutrino Factory facility study is at a much more advanced stage than that for the Muon Collider. To date there have been four studies of the Neutrino Factory: Study 1 [6] (sponsored by FNAL), Study 2 [9] (sponsored by BNL), Study 2a [10] (sponsored in part by the APS Neutrino Physics Study) and the International Scoping Study (ISS) [18] (sponsored by CCLRC in the UK). However, for the Neutrino Factory to be a realistic option for the field requires the continuation of an energetic R&D program leading to the publication of a Reference Design Report in 2012. Among the strengths of the ISS were an integrated, international collaboration and an integrated approach to the study of the accelerator complex, the neutrino detectors, and an evaluation of the physics performance of the facility. These elements are being continued in the International Design Study for the Neutrino Factory (the IDS-NF), which brings together the various national and regional Neutrino Factory design teams.

The primary goals of the IDS-NF are to:

- deliver a Reference Design Report for the NF accelerator complex and its neutrino detectors by 2012
- estimate the cost of the facility at the 50–75% level
- identify possible staging scenarios
- consider possible sites for the accelerator complex and neutrino detectors, taking into account, where appropriate, the existence of suitable infrastructure

Specifications for the accelerator systems developed by the Accelerator Working Group of the ISS are described in [18]. A schematic diagram of the ISS baseline is shown in Fig. 4 and the main parameters of the various sub-systems are defined in Table 5. The baseline specification for the stored muon energy is 25 GeV and the facility will deliver a total of 10^{21} useful muon decays per year. The baseline specification for the storage rings is that both signs of muon can be stored simultaneously.

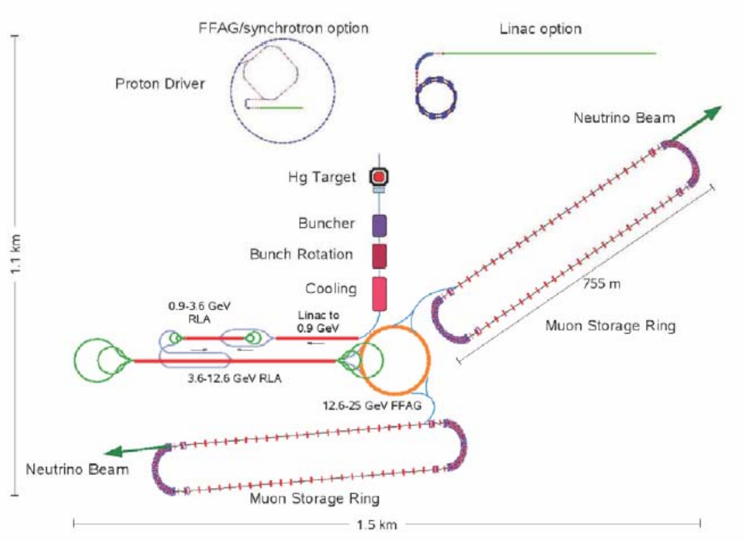

Fig. 4. Diagram of the IDS-NF baseline NF configuration.

Table 5: Baseline parameters for the sub-systems that make up the Neutrino Factory accelerator complex. The principal interface parameters are shown in bold face.

Baseline specification for the Neutrino Factory accelerator complex			Version
Sub-system	**Parameter**	**Value**	**2007/1.0**
Proton driver	Average beam power (MW)	4	
	Pulse repetition frequency (Hz)	50	
	Proton kinetic energy (GeV)	10 ± 5	
	Proton rms bunch length (ns)	2 ± 1	
	Number of proton bunches per pulse	3	
	Sequential extraction delay (μs)	≥ 17	
	Pulse duration, liquid-Hg target (μs)	≤ 40	
Target: liquid-mercury jet	Jet diameter (cm)	1	
	Jet velocity (m/s)	20	
	Solenoidal field at interaction point (T)	20	
Pion collection			
Tapered solenoidal channel	Length (m)	12	
	Field at target (T)	20	
	Diameter at target (cm)	15	
	Field at exit (T)`	1.75	
	Diameter at exit (cm)	25	
Decay channel	Length (m)	100	
Adiabatic buncher	Length (m)	50	
Phase rotator	Length (m)	50	
	Energy spread at exit (%)	10.5	
Ionisation cooling channel	Length (m)	80	
	RF frequency (MHz)	201.25	
	Absorber material	LiH	
	Absorber thickness (cm)	1	
	Input emittance (mm rad)	17	
	Output emittance (mm rad)	7.4	
	Central momentum (MeV/c)	220	
	Solenoidal focussing field (T)	2.8	
Acceleration system	Total energy at input (MeV)	244	
	Total energy at end of acceleration (GeV)	25	
	Input transverse acceptance (mm rad)	30	
	Input longitudinal acceptance (mm rad)	150	
Pre-acceleration linac	Final total energy (GeV)	0.9	
RLA(1)	Final total energy (GeV)	3.6	
RLA(2)	Final total energy (GeV)	12.6	
NFFAG	Final total energy (GeV)	25	
Decay rings	Ring type	Race track	
	Straight-section length (m)	600.2	
	Race-track circumference (m)	1,608.80	
	Number of rings (number of baselines)	**2**	
	Stored muon energy (total energy, GeV)	**25**	
	Beam divergence in production straight (γ^{-1})	**0.1**	
	Bunch spacing (ns)	**≥ 100**	
	Number of $\mu^{\pm}$ decays per year per baseline	**5×10^{20}**	

The detector for the Neutrino Factory is optimised for the search for leptonic-CP violation, the determination of the mass hierarchy, and the measurement of θ_{13} through the detection of the "golden channel" ($\nu_e \rightarrow \nu_\mu$). In order to accomplish this, two detectors located at different baselines are employed. A detector with a fiducial mass of 50 kT is located at an intermediate baseline (3000–5000 km) and a second detector of fiducial mass 50 kT is located at a long baseline (7000–8000 km). The longer baseline presents some challenging underground engineering issues for the muon storage ring that points in this direction. These issues will be discussed below.

The U.S. contribution to the IDS-NF will focus on the following areas:

- Proton driver
- Targetry and target stations
- Pion capture and muon phase rotation
- Ionization cooling
- Accelerator systems
- Site-specific underground engineering issues for the muon storage rings
- Magnetization concepts for neutrino detectors

The first four items are expected to be identical (or very similar) to the facilities needed for the Muon Collider complex and are covered in more detail in the MC ZDR section of this document. Of course, since we are developing a Reference Design Report for the Neutrino Factory, these sections must meet the needs of the NF RDR with respect to specifics and will thus go into more depth than would normally be expected for a ZDR.[6]

4.1 Proton Driver

U.S. participants in the IDS-NF will explore a NF proton driver based on the Project X linac design being developed at Fermilab. The incremental effort required for the U.S. contribution to the IDS-NF proton driver design will be to coordinate with the Project X design team to determine possible modifications to the facility that would be needed to meet the requirements of the NF (while also meeting the specifications demanded by the MC). It is expected that small rings for bunch manipulation will be necessary for the NF and their design and specifications (compatible with the Project X design) will be included in the NF RDR.

4.2 Targetry and Target Station

As was mentioned above, the MERIT experiment was a tremendous success and sets the foundation for the high-power target for the facilities that we are studying. The design of the target station itself is already at a relatively advanced stage from the work done in NF Studies 1 and 2. With the input from the MERIT experiment, the U.S. contribution to the IDS-NF in this area will be on more advanced simulations to set definitive benchmarks for the NF/MC target system[7]. The second aspect of this task will be to make the next

[6] Only the costs for this "incremental" effort are counted here.
[7] At present, we believe that the NF and MC target station designs are identical.

iteration on the facility design (following the ORNL/TM-2001/124 technical report) and to develop detailed engineering details of component parts of the system such as the target solenoid.

4.3 Pion capture and Muon Phase Rotation

After the target station, the front end of the NF must capture the pions, allow them to decay into muons, bunch the muons and then reduce the muon bunch energy spread. At our present level of understanding of the Neutrino Factory and the Muon Collider, we believe that a single design of the capture, bunching and phase rotation systems can accommodate the requirements of both facilities. For the NF-RDR, we will deliver an engineering design for the front end that will include magnet designs, a discrete (stepped-frequency) RF system, and a realistic representation of all absorbers and windows utilized in the system.

4.4 Ionization Cooling Channel

The baseline muon ionization cooling system for the NF is the Study 2a cooling channel. Compared with the earlier Study 2 design (being implemented in MICE), the baseline channel takes advantage of design improvements in the downstream acceleration systems that permit a larger emittance beam to be transported. The main difference between the present baseline and the Study 2 version is that we now employ a simpler LiH absorber design instead of a LH_2 absorber.

As noted, MICE is testing the earlier Study 2 cooling channel, which uses LH_2 absorbers and provides more cooling, but at higher cost. Plans for the MICE experiment call for also investigating LiH absorbers, which will be of great value to the IDS-NF effort. Indeed, results from the MICE experiment will play a seminal role in defining the engineering specification for the cooling channel in the NF RDR.

In addition to our baseline configuration, we intend to study two alternatives:

- hydrogen gas absorbers in place of LiH
- the helical cooler concept

If, in the early stages of our design study, either of these concepts shows promise of giving advantages in either performance or cost over the baseline, we will investigate it more thoroughly for the NF RDF and would switch our technology choice if appropriate. Any such decision must be finalized by 2011 at the latest.

4.5 Accelerator Systems

The design of the NF acceleration systems is already at a relatively advanced stage. A detail of the acceleration scenario is given in Fig. 5 and consists of:

- a pre-accelerator linac (0.14 to 0.9 GeV)
- a 4.5-pass, 0.6 GeV per pass RLA (0.9 to 3.6 GeV)
- a 4.5-pass, 2 GeV per pass RLA (3.6 to 12.6 GeV)
- a non-scaling FFAG (12.6 to 25 GeV)

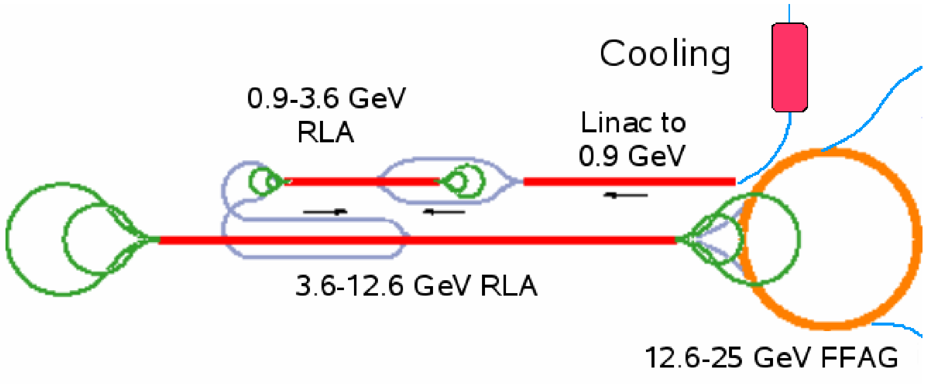

Fig. 5. IDS-NF Baseline acceleration scenario.

Within the IDS-NF, the main U.S. contribution will be to prepare an engineering design foundation including the following aspects:

- Definition and design of beam lines or lattices for
    - Linac
    - RLAs
    - FFAG
- Development of full component lists and detailed specifications for each system
- Studies of beam loading in FFAGs
- Resolution of physical interferences, e.g., beam line crossings, by developing floor coordinates for major components

4.5.1 *201 MHz rf cryomodules*

The acceleration system makes use of 201-MHz superconducting cavities. Studies of suitable manufacturing and processing techniques will be carried out, initially using 500 MHz model cavities, which can easily be tested at Cornell. Initial tests of atomic layer deposition (ALD) techniques[8] to reduce dark current emission have been encouraging and these will be pursued. Because of their large size, fabricating 201-MHz superconducting cavities from bulk Nb is very unattractive. Explosion-bonded Nb on copper looks like an attractive possibility and is already under study at Cornell.

R&D on cryomodule design will also be pursued as resources permit. Quantifying the impact of fringe fields on cavity operation is an area where we would like to make progress, as it has a big impact on component spacing.

4.6 Site-Specific Underground Engineering for the Decay Ring

Due the size (755 m) of the muon decay ring and the steep angle (~30°) at which it must point to aim at the long-baseline (7000–8000 km) detector, the underground engineering

[8]Developed at ANL and tested at Jlab.

aspects of such a design are formidable. One component of the U.S. contribution to the IDS-NF will be to study the problem of siting such a facility at Fermilab.

4.6.1 *Construction scope and definition of underground engineering*

Assumptions to be used for defining the construction project scope include:

- all underground structures (tunnels, caverns, and intersections) will be of "modest-span" (between 2 and 4 m in width).
- at least some of these underground facilities will be aligned on steep gradients, at depths of up to 0.5 km below grade
- a design brief can be generated in-house, with support from the collaboration and laboratory ES&H, and accomplished in a six-month period. The brief will be relatively simple, consisting of an initial set of single-line drawings showing the underground space envelopes and a list of key as-built requirements consistent with the technical needs and conventional infrastructure.
- in-house supervision will be utilized for the duration of field work[9]

To fully develop the underground engineering R&D plan, we will convene an expert panel comprising a senior representative with a design contractor background, a senior representative with a construction contractor background, and an independent technical consultant.

Although the Fermilab site has some very positive attributes, there are also some significant issues that will need to be addressed in the NF RDR. These include:

- isolating the facilities from the regional aquifers
- limitations due to rock fall occurrence
- enhancing the tunnel floor stability
- identification of "best existing" or development of improved methods to mine rock on steep slopes

Carrying out the engineering effort we outline in Appendix 4 during the early years of concept development of the project will not only help reduce the construction cost, duration and contingency, but will also help limit the number of design iterations.

The twelve tasks identified in Table 6 will accomplish the following;

- define the *in situ* ground conditions to the full project depth (Tasks 1–6)
- identify adverse ground behaviors, and provide a rationale for selecting design and construction options (Tasks 7–8)
- support the development of a basis-of-estimate and perform a first-order cost, schedule, and risk analysis (Tasks 9–11)
- Provide expert recommendations for further study and design work (Task 12)

[9] 1 FTE for 1 year.

Table 6. Tasks for underground engineering effort.

Task	Description
1	Preparation of design brief
2	Best value procurement of geo-engineer and expert contractors
3	Geological desk studies
4	External review to support scoping of follow-up work
5	Best value procurement of a geotechnical engineering and drilling contractor
6	Geotechnical field and laboratory studies
7	Ground characterization
8	Constructability/optimization review
9	Basis-of-estimate review
10	Best value procurement of an underground estimating contractor
11	Independent cost and schedule
12	Summary of findings and recommendations

4.7 Magnetization Concepts for Neutrino Detectors

All detector concepts for the Neutrino Factory require a magnetic field in order to determine the sign of muon (or possibly the electron) produced in a neutrino interaction. For the baseline detector, this is done with magnetized iron. Technically, this is very straightforward, although for the 50 kT baseline detectors it does present challenges because of their size. The cost of this magnetic solution is believed to be manageable.

Magnetic solutions for other NF detectors will be much more challenging. We have considered magnetizing volumes as large as 60,000 m^3 for a liquid-argon detector or a totally-active scintillator detector (TASD). For the cases of the TASD and the LAr approach currently being studied by U.S. and Canadian groups, providing the required magnetic volume with 10 solenoids of roughly 15 m diameter × 15 m length has been considered, with the solenoids configured into a magnetic cavern as shown in Fig. 6. We have considered a number of field strengths, but chose the baseline to be 0.5 T.

The problem with building very large conventional superconducting solenoids is that 90% of the cost goes into the cryostat, which must withstand enormous vacuum loading forces. We avoid this problem in our design by using the superconducting transmission line (STL) concept that was developed for the Very Large Hadron Collider superferric magnets [20]. The solenoid windings thus consist of a superconducting cable that is confined in its own cryostat. Each solenoid comprises 150 turns and requires about 7500 m of cable. There is no large vacuum vessel and, since the STL does not need to be close-packed in order to reach an acceptable field level, access to the detectors can be made through the winding support cylinder. As part of the IDS-NF RDR we will include work on this magnet concept. The scope will include:

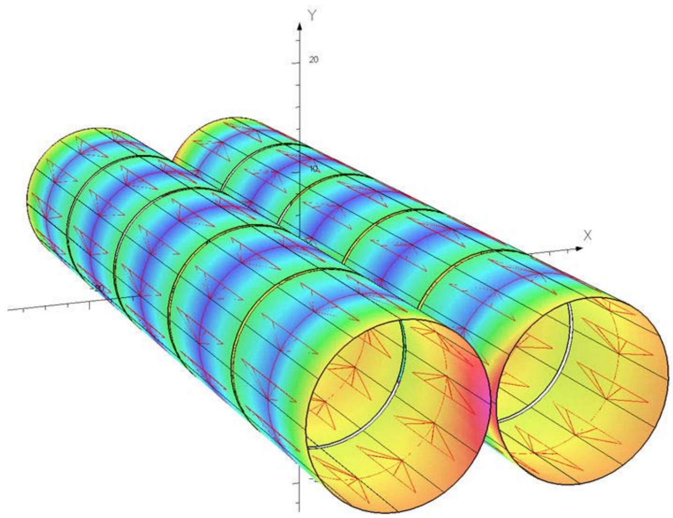

Fig. 6. Magnetic cavern configuration.

- redesign of a superconducting transmission line for this application
- conceptual design of a full-scale (15 m diameter) 3-turn prototype
- engineering design and procurement for a prototype STL device
- assembly and commissioning of the prototype
- prototype test and evaluation

5. COMPONENT DEVELOPMENT AND EXPERIMENTS

The goal of our proposed component development and experimental R&D program is to:

- establish the viability of the concepts and components used for the MC-ZDR and NF-RDR designs,
- establish the engineering performance parameters that can be assumed in the design studies, and
- provide a good basis for cost estimates.

The component R&D will also provide a basis for the post-MC-ZDR R&D tests and experiments that will be needed before a MC can be built.

With the successful completion of the MERIT target experiment, the main outstanding technical challenge that is common to both NF and MC front-ends is to demonstrate the viability and performance of the technologies needed for a transverse ionization cooling channel. The MICE experiment at RAL will provide the key demonstration of the operation of a short cooling channel section, and we consider it a high priority to complete this experiment in time to inform both the NF-RDR and the MC-ZDR.

The main additional challenge that must be met for a successful MC-ZDR is to arrive at a design of an appropriate 6D cooling channel that is based on technologies and parameters in which we have confidence. At present, there are several candidate cooling channel designs that are being studied. All these designs rely on RF operating in strong magnetic fields that confine the muons within the channel and provide radial focusing. Our MuCool R&D program has demonstrated that the maximum gradients achievable in normal conducting vacuum rf cavities made of copper are reduced when the cavity is operated in axial magnetic fields of a few tesla. Hence, before a cooling channel technology can be selected for the MC-ZDR design (or for the NF-RDR design) it is important to provide a proof-of-principle demonstration of the operation of the rf cavity within the particular magnetic field configuration for the assumed cooling channel, and to establish its maximum achievable rf gradient. Once we have demonstrated one or more rf solutions, the next step will be to build and bench-test short cooling sections. This will inform the ZDR cooling channel simulations by ensuring that the practical engineering details that affect performance are understood, by establishing viable cooling channel parameters, and by providing a good basis for cooling channel cost estimates. The bench-test experiments will also prepare the way for an eventual (post-ZDR) 6D cooling channel demonstration experiment.

5.1 MICE

The Muon Ionization Cooling Experiment (MICE), which is hosted at Rutherford Appleton Laboratory in the UK, has been designed and is being constructed, commissioned, and operated by an international collaboration in which NFMCC institutions play a crucial role, contributing to every aspect of the experiment.

5.1.1 *The MICE Program*

The goals of MICE are to:

- engineer and build a section of cooling channel (of a design that can give the desired performance for a Neutrino Factory) that is long enough to provide a measurable (≈10%) cooling effect, but short enough to be moderate in cost;
- use particle detectors to measure the cooling effect with an absolute accuracy of 0.1% or better;
- perform measurements in a muon beam having momentum in the range 140–240 MeV/c, in which particles can be tracked individually, one particle every 100 ns or more.

The MICE apparatus is shown schematically in Fig. 7. It consists of an upstream instrumentation section to precisely measure incoming muons, a short cooling channel section consisting of absorbers and rf cavities in a solenoid lattice, and a downstream instrumentation section to precisely measure the outgoing muons**.** The MICE apparatus can be viewed as a quite general test-bed for ionization cooling ideas. The ionization-cooling lattice cell comprises eight superconducting coils that can be variously powered to create "super-FOFO" [9] (field direction alternating each half-cell) or solenoid-type (field directions constant) optics, and the currents can be tuned to characterize cooling

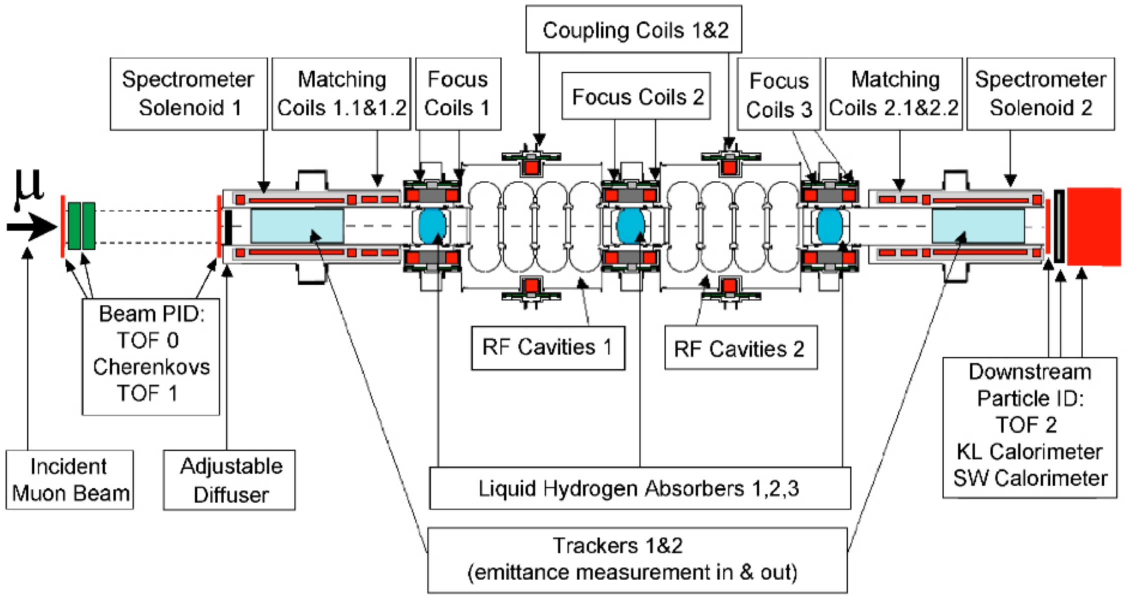

Fig. 7: Schematic drawing of MICE apparatus, comprising a muon beam line at left (not shown), particle-identification systems, and input and output spectrometers surrounding a single ionization-cooling lattice cell.

performance with a variety of beta functions. The MICE goals require that this be done in order to validate the Monte Carlo simulations that are used to design such cooling channels.

MICE is located in a new purpose-built muon beam at the ISIS synchrotron. Preparing for MICE has required the development and installation of a tunable pion/muon beam line as well as a target that can be dipped into the ISIS beam as needed. These are now in place, and the process of installing and commissioning the beam and particle-identification instrumentation is under way. The MICE cooling channel will be gradually built up and commissioned over the next several years as indicated schematically in Fig. 8. This stepwise approach has the virtue of allowing the measurement systematics to be thoroughly evaluated and optimized. We anticipate that MICE will be completed by the end of 2011. At this time, a transverse cooling channel suitable for a NF would have been demonstrated, and MICE results will be used to inform the NF-RDR. Beyond this initial MICE program, there is the possibility of using the MICE apparatus to begin to explore some aspects of 6D cooling that are relevant to the design of MC cooling channels, and that can inform the MC-ZDR studies.

A simple test of the six-dimensional ionization-cooling concept can be made by inserting a wedge absorber (composed, e.g., of LiH) into a beam having suitable dispersion, and measuring the effect on the beam. This may be possible in MICE either by tuning the incoming beam so as to produce the desired dispersion or by selecting out of the distribution of incoming muons an ensemble that has dispersion matched to the

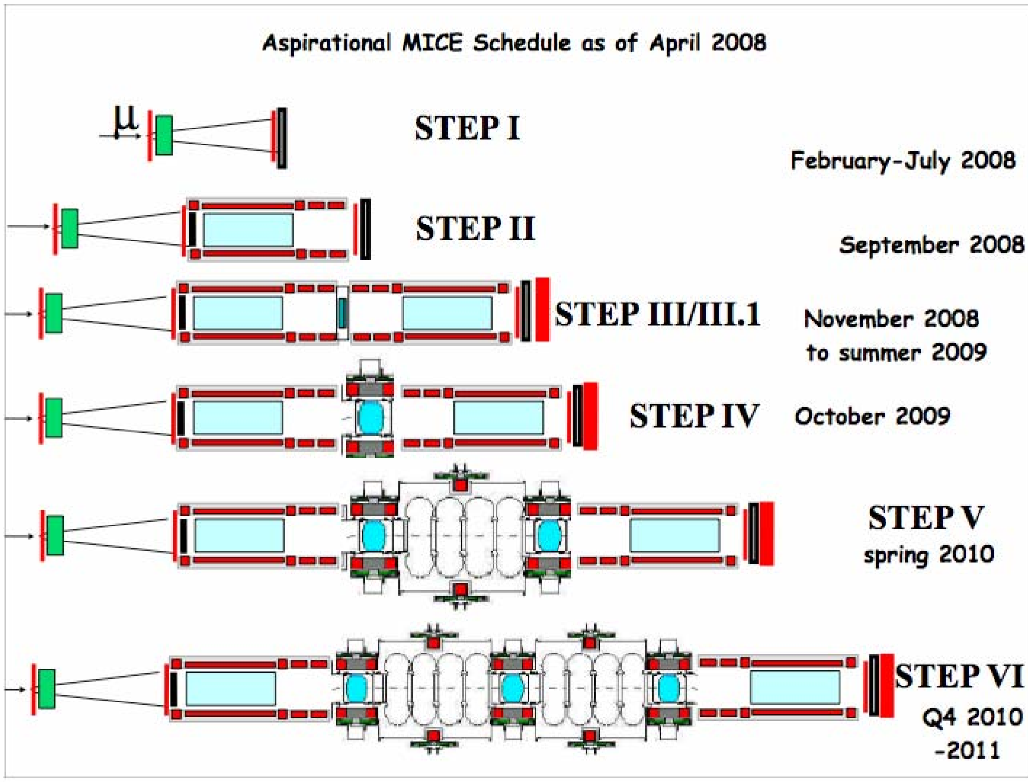

Fig. 8. Projected schedule of MICE experiment at RAL, showing stepwise execution of the experiment.

configuration of the wedge absorber. This concept needs further study to evaluate both its feasibility and the degree to which it could constitute an incisive demonstration of six-dimensional cooling.

As will be discussed later, a more ambitious six-dimensional ionization-cooling test could be considered in which the MICE beam and detectors are used to evaluate and study an actual prototype of a six-dimensional cooling channel. Thus MICE has been discussed as a possible site for the proposed MANX experiment [39], as well as for other six-dimensional cooling lattices that could be considered for such a test. For example, a section of an RFOFO ring or "Guggenheim" cooler could be built and inserted into MICE, or such a lattice could perhaps be approximated using components already being built for MICE. This more ambitious cooling test would be beyond the timescale of the MC-ZDR, and indeed the ZDR study results would be used to precisely define the required goals for it. We foresee design work towards a 6D cooling experiment proceeding in parallel with the MC-ZDR.

The official MICE US deliverables are:

- Spectrometer solenoids (2), including engineering, fabrication, testing, and field-mapping
- Assembly of scintillating-fiber planes (15) for fiber-tracking spectrometers
- AFE-IIt readout boards, VLPCs, and VLDS interface modules for fiber-tracking readout
- Design, fabrication, and commissioning of VLPC cryostats (4) for fiber-tracking spectrometers
- Fiber-tracking readout system integration and commissioning
- Fabrication, installation, and commissioning of two Cherenkov counters
- RFCC modules (2) comprising 8 RF cavities and 2 Coupling Coils
- Scintillating-fiber beam position/profile monitors (4 planes)
- Design and fabrication of LiH absorbers
- Participation in MICE operations and analysis

Although not yet part of the formal experimental plan, there is the possibility of further extensions to MICE, including beam tests of a LiH wedge absorber or other 6D cooling channel component.

5.2 RF Systems

5.2.1 *Cooling channel rf*

As already mentioned, all cooling channels rely on rf cavities operating in high magnetic fields, so it is crucial to demonstrate that the technology is feasible and reliable.
There are currently four potential paths to achieving the required high gradients in multi-Tesla magnetic fields for normal conducting rf cavities:

- Treating cavities with superconducting rf cleaning techniques has shown positive results. A 201 MHz MuCool cavity was processed with electro-polishing and high pressure rinsing and tested in the MuCool Test Area (MTA) at Fermilab. The cavity reached its design gradient with essentially no conditioning. Cavity tests are expected in the coming year to establish whether the cavity can be operated with sufficiently high gradient while immersed in a multi-tesla magnetic field. If the results prove promising, further testing on an 805-MHz model of the 201-MHz cavity is planned, as well as testing of a 201-MHz prototype cavity for a 6D-cooling channel.

- Treating cavities with atomic layer deposition (ALD) consisting of monolayer chemical deposition of various materials on cavity surfaces. Initial tests of a superconducting cavity coated with 5 nm of ZrO_2 plus 30 nm of Pt was performed at Jlab. The ALD treatment greatly reduced the dark current while maintaining the achievable cavity gradient. The next step will be to test a similarly treated normal conducting cavity in a magnetic field to evaluate its performance. To this end, we anticipate building an 805-MHz cavity for ALD coating and testing in the 5-T solenoid at the MTA. If the results are positive, a prototype 201-MHz cavity for a 6D-cooling channel (the cavity mentioned above) will be ALD processed and retested. The durability of ALD must also be determined.

- “Magnetic insulation” is a recently considered approach for reducing cavity breakdown. By arranging the magnetic field to be parallel to the high-gradient surfaces, it is expected that the emitted electrons can either be inhibited from leaving the surface or be guided to surfaces in regions of low gradient, thereby suppressing breakdown. A study of cavity breakdown in a magnetic field as a function of field direction using a rotatable cavity is needed to provide a test of this concept. If successful, this initial test would be followed by the design, construction and testing of an 805 MHz cavity incorporating magnetic insulation.

- It has been demonstrated that a cavity pressurized with ~100 bar of hydrogen gas (High Pressure rf, HPRF) has suppressed breakdown up to gradients approaching 60 MV/m, and that this performance is not affected by magnetic fields. However, such a cavity has never been tested with beam. In pure hydrogen, ionization electrons will remain in the gas for a significant portion of the rf pulse, being accelerated back and forth by the rf fields, and transferring the electromagnetic energy stored in the cavity to the gas through collisions. Depending on the intensity of the incident beam, the Q of the cavity could be reduced by several orders of magnitude. It is likely that introducing another gas species may capture these free electrons. However, a good candidate gas has not yet been found. (SF_6 is frozen at LN_2 temperature, and also may form hydrofluoric acid.) In addition, it must be demonstrated that the large number of ions created do not present a problem. A beam test of a HPRF test cavity is presently being prepared at the MTA. If successful, this initial test would be followed by the design, construction and testing of a prototype 805-MHz HPRF cavity.

In addition to investigating these specific paths, which will be done in the first two years of the proposed program, the exploration of alternative cavity materials and surface coatings using replaceable buttons in a dedicated test cavity will continue. Striking qualitative differences in materials have already been observed, although initial attempts to quantify the resistance of alternative materials to breakdown damage in the presence of high magnetic fields have been compromised by continued breakdown elsewhere in the copper test cavity. In particular, the beryllium components in the cavities are remarkably undamaged even after heavy arcing, and other high-strength, high-melting point materials appeared to be similarly resistant. New test cavities capable of exploring the conditioning limit with higher surface fields and more stored energy may provide quantitative differences and reveal which physical properties best correlate with breakdown resistance in vacuum cavities.

5.2.2 *Superconducting rf*

Once the muon beams are cooled sufficiently to fit into the acceptance of a "conventional' accelerator, SRF technology is an attractive choice for rapid acceleration at high gradients. These acceleration stages are a significant cost driver in a Neutrino Factory or Muon Collider. Studies to date have assumed gradients and Q values demonstrated using sputtered coatings of niobium on copper, as was used successfully at LEP and elsewhere. Recent promising results using ALD and energetic condensation indicate the possibility of producing high quality "bulk-like" niobium thin films, and, more tantalizingly, the possibility of creating superconducting compounds that are hard to form by traditional methods. These developments should lead to higher available gradients with better efficiency (higher Q_0), improving overall muon yield and reducing rf power and structure costs. To realize these gains the five-year plan should include tasks to evaluate and optimize these promising coating technologies on small samples, test cavities and finally full-featured low frequency cavities with realistically large surface area.

In the final stages of acceleration for a Muon Collider, the beams may fit inside conventional high-frequency accelerating structures. However, the high bunch intensity, especially if bunches are merged, will place extreme demands on the superconducting rf technology. Structures optimized for this application will be needed, including such features as increased stored energy, low wakes, and high power handling capability. Given the long gestation time of new superconducting rf structures and ancillary systems, the development of these optimized structures must begin now.

5.3 Magnets

Neutrino Factory and Muon Collider accelerator complexes require magnets with quite challenging parameters. In particular, the cooling channel cost and performance will be determined in part by magnet costs and by the fields that can be reasonably delivered in the high-field solenoids at the end of the cooling channel. The magnet R&D that we propose pursing to inform the MC-ZDR consists of

(i) HTS solenoid R&D to assess the parameters that are likely to be achieved with a further specified R&D program, and hence the role of HTS magnets in the cooling channel baseline design

(ii) HCC magnet R&D to assess the feasibility of this type of cooling channel and eventually build a demonstration magnet for an HCC test section (see Section 5.5.2)

(iii) open mid-plane dipole magnet R&D to assess the viability of this magnet type for the collider ring

(iv) other magnet studies to inform choices, parameters and cost estimates for the target-station solenoid and accelerator magnets.

5.3.1 *High-field cooling channel solenoids*

Very high field solenoids with on-axis fields in excess of 30 T and apertures on the order of 50 mm, are part of the baseline design for the MC final cooling channel. The technology for building these magnets using HTS has been demonstrated in the 20 T regime, but it needs to be extended to higher fields with good field quality, and with reliable construction at a reasonable cost.

Thus, the goals for our proposed HTS magnet R&D are:

(i) based on initial HTS conductor and magnet R&D, establish the R&D issues that must be addressed before high-field (B > 30 T) HTS solenoids can be built that are suitable for the low-emittance sections of a muon cooling channel, and hence

(ii) assess the likelihood that suitable high-field HTS solenoids will be available within a few years and, if so, their likely cost and performance.

More explicitly, we would

- Develop with accelerator designers a set of functional specifications for a high-field solenoid, including minimum aperture, length, body and end field quality, alignment, field strength range, power requirement (conventional and hybrid), and cost.

- Summarize the ongoing status of conductor properties (HTS, A15, Nb-Ti, normal strands, and cables), including maximum current density *vs*. field (or field direction for tapes) and temperature; longitudinal, bending, and transverse stress/strain tolerances; quench protection and cooling requirements; cabling capabilities and performance; and conductor insulation materials. Also, as needed and not otherwise supported by existing data or the proposed national HTS program, evaluate new conductors and insulation materials.

- Develop conceptual designs for magnets that meet our specifications from task 1 and conductor properties from task 2. Investigate magnetic, mechanical, magnet cooling, power and quench protection issues of HTS and hybrid designs.

- Build and test representative HTS and hybrid-insert models to develop and demonstrate HTS coil technology and performance, and to study model magnetic, mechanical, thermal and quench properties.

- Based on the results of tasks 1–4 present a plan (conceptual design, time, effort, cost) to build a 1 m long >30 T solenoid in 2013–2015.

5.3.2 *Helical cooling channel magnets*

The helical cooling channel requires a solenoid with superimposed helical dipole, quadrupole, and sextupole fields. A novel approach is to use a helical solenoid (HS) to generate the required field components. The basic concept is to use circular short coils shifted in the direction transverse to the *z* axis. All coil centers lay on a helical beam orbit and are equally distributed along *z*. Because the orbit is tilted relative to the coils, they simultaneously generate longitudinal and transverse field components. In contrast to a large bore system, where the longitudinal and transverse field components are controlled by independent windings, the small bore system has a fixed relation between all components for a given geometry. Thus, to obtain the necessary cooling effect, the coil must be optimized together with the beam parameters.

In order to produce a practical helical cooling channel, several technical issues need to be addressed, including:

- magnetic matching sections for downstream and upstream of the HCC
- a complete set of functional and interface specifications covering field quality and tunability, the interface with rf structures, and heat load limits (requiring knowledge of the power lead requirements)

To prepare the way for an HCC test section we would:

- Develop, with accelerator designers, functional specifications for the magnet systems of a helical cooling channel, including magnet apertures to accommodate the required rf systems, section lengths, helical periods, field components, field quality, alignment tolerances, and cryogenic and power requirements. The specification will also consider the needs of any required matching sections.

- Perform conceptual design studies of helical solenoids that meet task 1 specifications, including a joint rf and magnet study to decide how to incorporate rf into the helical solenoid bore, corrector coils, matching sections, etc.

- Fabricate and test a series of four-coil helical solenoid models to develop and demonstrate the coil winding technology, pre-load and stress management, cooling, and quench protection for low-field sections based on Nb-Ti and/or Nb_3Sn cable. The proposed timeline for these studies is:
    - Nb-Ti model based on SSC cable and hard-bend winding in 2008
    - Nb-Ti models based on easy-bend winding and indirect coil cooling in 2009

  In addition, a set of coils based on hybrid Nb_3Sn-HTS superconductor may be developed for the high-field sections. This work would be supported by SBIR funding.

- Develop and test a "short" (one-quarter to one period) demonstration helical solenoid section capable of housing rf cavities in a cryostat (i.e., a helical cooling cryomodule). The associated timeline for this would be:
    - Conceptual design in 2010
    - Engineering design and construction and test in 2011–2012
    - Results of magnet test to be in time for MC-ZDR report in late 2012

5.3.3 *Collider ring magnets*

The collider ring will consist of arc dipoles, quadrupoles, correctors, and interaction region dipoles and quadrupoles. The arc dipoles should operate at high field in order to keep the ring circumference small, providing a larger number of crossings for a given number of stored muons and lifetime. These magnets must also operate in a high radiation and high heat load environment resulting from the muon decay electrons, which are preferentially swept into the magnet mid-plane. In order to avoid quenches, limit the cooling-power requirements, and maintain an acceptable lifetime, the superconducting coils must be protected from excessive energy deposition due to these decay electrons. Similar considerations apply to the arc and IR quadrupoles.

Despite the unique operating conditions that apply to the muon collider, many of the basic magnet R&D issues are similar to those presented by other high-energy accelerators. In particular, high operating field and large energy deposition are required for the LHC energy and luminosity upgrades. Therefore, the muon collider R&D effort in this area will be coordinated with ongoing development of high-field dipoles and quadrupoles for the LHC. In addition, some of the fundamental materials issues (high-field superconductors, radiation hardness, thermal margins, structural materials, electrical insulation, etc.) are common to different types of magnets, such as dipoles for the collider and solenoids for muon cooling. Therefore, materials R&D can and should be effectively organized through an integrated effort supporting various magnet R&D areas for the muon collider as well as other accelerator projects.

Two approaches have been considered in previous dipole designs:

- use of a thick absorber surrounding or internal to the vacuum chamber and protecting the coils
- a magnet design that moves the superconducting coils away from the mid-plane

The former approach requires a large magnet aperture, while the latter presents considerable challenges in terms of efficiency of field generation, mechanical support, and field quality.

The R&D effort for the collider magnets will include design analysis, technology development, and prototype fabrication. Its main sub-tasks will be to:

1. Compare design options for the arc dipoles, and identify a baseline magnetic, mechanical, and thermal design. This activity will benefit from previous studies of conventional and open mid-plane designs carried out for the muon collider as well as the LHC “dipole-first” IR upgrade scheme.

2. Compare design options for arc and interaction region quadrupoles, and select a baseline design. Similar to the dipole case, options considered in the past include large bore designs with thick liners and designs where the conductor is removed in the mid plane. In addition, conventional quadrupoles were considered, where

most of the decay energy can be absorbed by a cooled absorber outside the quadrupole.

3. Provide consistent sets of magnet parameters (aperture, length, integrated strength, tolerances on field errors) taking into account the radiation deposition issues, to be used as input for the machine optimization.

4. Define and implement technology tests in support of the magnet design and prototyping. These may include mechanical models, sub-scale coil tests, experiments to determine thermal margin and radiation lifetime, materials characterization, etc. This effort will also take advantage of collaborations with other ongoing R&D efforts (such as LHC upgrades) to carry out larger scale tests.

5. Design of the main magnetic elements (arc dipoles and quadrupoles, and IR quadrupoles), to a level sufficient to support preliminary cost estimates.

6. Provide cost estimates for further R&D and prototyping, and preliminary cost envelopes for magnet production.[10]

5.3.4 *Other magnet studies*

Fast-ramping synchrotron magnets. One novel muon acceleration concept utilizes a very rapid cycling synchrotron. In a proposed scenario using the existing Tevatron tunnel to accelerate muons from 30 to 750 GeV in 72 turns, each of the Tevatron half-cell's four main dipoles are replaced by three fast ramping dipoles that ramp at 550 Hz from –1.8 T to +1.8 T, interleaved with 8 T fixed superconducting dipoles [40]. These magnets would utilize 3 mm copper tubing and 0.28 mm grain-oriented silicon steel laminations, plus a 2% duty cycle, to mitigate eddy-current losses.

To demonstrate the feasibility of this approach, two 6 mm gap prototype dipoles would be built, the first 30 cm long and the second 6.3 m long. Thin grain-oriented silicon steel laminations are used in an EI transformer layout to minimize eddy-current and hysteresis losses. OPERA-3d will be used to simulate eddy-current and hysteresis losses, optimize magnet end shapes, and calculate sextupole fields resulting from eddy currents. Laminations would be slit and sheared and then finished using wire electron discharge machining (EDM).

This would be a two-year program, with the 30 cm long prototype dipole built in the first year and the 6.3 m long prototype dipole built in the second year.

Investigation of capture solenoid requirements. A capture solenoid magnet is required for both muon collider and neutrino factory schemes for focusing the production target pions. The design challenge for this magnet is to make a wide aperture 20 T solenoid in a very high heat load environment.

[10]More accurate estimates of production costs will be provided after prototype fabrication and test.

A magnet design has been developed for the "Study 2" report [9]. The design calls for a 20 T hybrid solenoid, with a resistive insert and a superconducting outer layer. Peak fields in the outer layer are approximately 15 T, necessitating the use of Nb_3Sn. While the design looks quite feasible, the conceptual design of this magnet should be re-evaluated including consideration of the operating cost of the conventional insert. An alternative conceptual design of a magnet using an HTS insert in place of the "Bitter insert" should be considered in light of recent progress in HTS conductor development.

<u>10-15 T solenoids needed for late-stage 6D cooling</u>. Initial 6D cooling can be done with magnetic fields in the range of 3 T. Magnet development for a HCC solution was already discussed above. The magnets for a Guggenheim or snake solution would be similar to those in MICE that have already been studied and are under construction, so no new initiative is called for. However, for the later stages of cooling, higher field compact solenoids of the order of 10–15 T are needed.

Fields on the order of 15 T can be attained using Nb_3Sn conductor. The required current densities need to be much higher than used in commercial magnets with these fields, but are comparable to those achieved in model accelerator magnets presently being built and tested at DOE laboratories. The essential features in these successful Nb_3Sn magnets are the use of Rutherford cable, reaction after winding, vacuum epoxy impregnation, and strong support and pre-compression.

Our R&D plan calls for developing designs that apply, insofar as possible, accelerator magnet methods to these solenoids. This will be followed by building and testing a sequence of model magnets. Some initial design work has already been done at LBNL on a high current density (520 A/mm^2) 12 T (axial) coil. Note that there is a large synergy between this development work and that previously described for the high-field sections of the HCC magnet system. Thus, part of the effort will be to coordinate these activities and apply the same design and construction principles as much as possible.

The goal of this activity is to determine the status and feasibility of these solenoids in time for the MC ZDR in 2012.

<u>Development of cost models or algorithms for specialized magnetic components</u>. Magnets will be one of the significant cost drivers for the MC. A fully designed MC will require hundreds of magnetic elements throughout the accelerator chain. We have identified those magnets that will require R&D in order to demonstrate that they will be ready in the MC time frame. For cost-estimating purposes and schedule estimates, however, many of the other magnet designs can be borrowed or extrapolated from existing designs or from general magnet experience.

Our plan is to develop a cost model algorithm to apply to those magnets whose designs can be based on previous or ongoing accelerator design studies, and then use it for the MC. In addition, we will develop a catalog for all magnet elements, including categorizing magnets of like function to facilitate cost studies.

5.4 Absorber Development

In addition to rf cavities and magnets, cooling channels require absorbers. These must be made of low-*Z* material, preferably hydrogen. Liquid hydrogen and solid LiH absorbers of approximately uniform thickness have been developed and will be tested in MICE. For 6D cooling, either high-pressure gas (in the case of the HCC) or wedge-shaped discrete absorbers (in the case of the Guggenheim channel) will be required.

5.4.1 *High-pressure hydrogen gas absorber*

In the case of pressurized cavities, the hydrogen gas that is introduced to suppress breakdown also acts as the absorber. Most issues associated with such gaseous absorbers are related to how the cavity operation will be affected by the ionization electrons created by the beam. These issues will be addressed by the rf program, as discussed earlier. However, pressure and safety windows for the beam to enter and exit must be designed. The windows must be thin enough to avoid excessive emittance blow-up, yet strong enough to hold the pressure. Clearly, the safety concerns related to the large volume of hydrogen used must be evaluated and then addressed.

5.4.2 *Liquid-hydrogen wedge absorbers*

6D cooling channels using periodic lattices employ wedge-shaped absorbers. These could be made of liquid hydrogen or lithium hydride. In most applications, performance is better with liquid hydrogen, although the difference is only critical toward the end of the MC cooling channel. The liquid-hydrogen containment and safety windows should be as thin as possible, and made from the lowest-*Z* materials possible. However, they must also be made from a material that does not become brittle at cryogenic temperatures or due to hydrogen embrittlement. Study of the use of AlBeMet (an alloy of beryllium and aluminum), is needed. Several ideas have been suggested for the construction of liquid-hydrogen absorbers with wedge, or wedge-like, shapes. These will be evaluated by means of engineering development and simulation studies.

5.4.3 *LiH wedge absorbers*

LiH has several advantages over liquid hydrogen. It is much easier to form into a wedge and it does not need to operate at cryogenic temperatures. It does not need pressure containment windows and, having a higher density, it provides more energy loss per unit length (making it well-matched to a low-beta lattice). However, the equilibrium emittance, for a given beta and momentum, is higher than for hydrogen.

LiH can be obtained in a number of forms, but providing it as a sintered solid is the form most suitable for our application. Its thermal conductivity is not extremely high, but can be well controlled. LiH in sintered form reacts mildly with water vapor and will need to be suitably protected. Parylene coating of LiH (a chemical vapor deposition process) provides a strong protective coating and water-vapor barrier, and is commercially available. Edge cooling depends strongly on thermal conductivity and also depends on the quality of the thermal contact. Helium gas cooling may need to be studied. As noted earlier, LiH disk absorbers and perhaps also wedges will be tested in MICE.

5.5 Cooling Section Tests and Experiments

Approximately one year before the end of the MC-ZDR study, we anticipate making a choice of which cooling channel scheme to adopt for the baseline design, end-to-end simulation, and costing. The various candidate cooling schemes will become more or less attractive as viable options depending on the results of the rf tests described in Section 5.2. We anticipate critical results from the rf tests in the first two years of our R&D program, at which time we will proceed with building short cooling sections for either one cooling scheme or perhaps two cooling schemes. The cooling sections would be tested in the MTA to determine their viability and operating parameters. In the following, we assume that two 6D cooling sections will be built and tested—a Guggenheim channel using magnetic insulation, SC treatment and/or ALD, and a Helical Cooling Channel using HPRF.

5.5.1 *Guggenheim test section*

The R&D path that would lead to a test of a Guggenheim section with magnetically insulated normal conducting rf cavities using superconducting cavity treatment techniques plus ALD is as follows:

> Year 1–2: Successful 805-MHz cavity tests separately demonstrating the effects of superconducting cavity treatment, ALD, and/or the effect on maximum achievable gradient from magnetic field direction. Also, successful end-to-end simulation of a Guggenheim cooling channel based on the established rf parameters and technologies.
>
> Year 3: Designing the test section. The outcome of the design work will inform the MC-ZDR baseline decision.
>
> Year 4–5: Build and test a Guggenheim test section in the MTA. Test results would validate the engineering performance at the end of the MC-ZDR study.

5.5.2 *Helical cooling channel test section*

The R&D path that would lead to a test of a HCC section with HPRF would be:

> Year 1: Successful beam test of the existing 805-MHz HPRF test cavity in the MTA, and successful HCC few-coil model tests to validate the winding technology and magnet concept.

Year 2: Successful beam test of a realistic 805-MHz HPRF cavity in the MTA and successful end-to-end simulation of a MC HCC cooling channel section. Begin HCC test section design.

Year 3: Complete design of test section. The outcome of the design work would inform the MC-ZDR baseline decision.

Year 4–5: Build and test the HPRF test section in the MTA. Test results would validate the engineering performance at the end of the MC-ZDR study.

5.5.3 *Preparations for a 6D cooling demonstration experiment*

The basic physics of transverse cooling will be demonstrated by MICE, and the basic physics of 6D cooling can most likely be demonstrated by using a wedge-shaped absorber in the MICE equipment, selecting tracks to create a "virtual" beam with dispersion at that wedge, and measuring the 6D emittances before and after using the MICE detectors.

A full 6D demonstration experiment would clearly be a major undertaking, and could not be finished in the next four years. We therefore do not plan to commit to one until after the basic technology choices have been made, i.e., towards the end of the ZDR process. Nevertheless, conceptual studies of the options will be undertaken.

It is obviously impractical to demonstrate all stages of the cooling without building the complete system. The following list of possible experiments is aimed to cover examples of cooling at three different stages—the initial 6D cooling, the final 6D cooling, and the final 4D cooling. In the first case, there are three technology options: a Helical Cooling Channel, periodic lattices with alternating bending (snake), or periodic lattices with continuous bending (Guggenheim). In addition there is the choice of gas- or vacuum-filled rf. In the later stages, the options are more limited. The following list will serve to illustrate the range of possible demonstrations.

a) A high pressure hydrogen gas filled HCC for early 6D cooling to the order of 2000 π mm mrad.
b) A high pressure hydrogen gas filled periodic lattice (snake or Guggenheim) for early 6D cooling to the order of 2000 π mm mrad.
c) A vacuum rf periodic lattice (snake or Guggenheim) for early 6D cooling to the order of 2000 π mm mrad
d) A vacuum rf periodic lattice (snake or Guggenheim) for late 6D cooling to the order of 400 π mm mrad
e) A high-field solenoid 4D lattice for cooling to the order of 25 π mm mrad

Item c) would be the least expensive, since it involves equipment similar to that being built for MICE. Items a) and b) might be able to use the MICE detector equipment, but would be more expensive because of the use of high-pressure hydrogen and, in item a), the construction of a helical magnet system with integrated rf. Item d) may have a high priority as it demonstrates 6D cooling to lower emittances than those explored at MICE, but it will require development of detectors capable of measuring these smaller emittances. It is possible that such measurements could be made with a gas TPC in the MICE detector solenoids. Item e) would be an even greater measurement challenge that has not yet been studied. It will also require at least one solenoid with a strength on the order of 50 T. A device using HTS to reduce the power consumption appears to be the most attractive option.

To prepare for such an experiment, which we anticipate being performed after the ZDR is completed, conceptual designs and cost estimates are required for:

- beam and detector technologies that will measure the cooling fat the different stages
- integration of the cooling channel components for each potential experiment

5.6 Target System

While the MERIT experiment was successful as a proof-of-principle for using a free mercury jet as a target for a multi-MW proton beam, that experiment was *not* a prototype for a production target system. Hence, we need a program of continued R&D that builds on the MERIT experiment, and on the systems engineering studies performed in 2000–2001 as part of NF Studies 1 [6] and 2 [9]. The development of a second-generation target station for the NF and MC will require investigation into a number of technical issues. Some of these represent challenges identified in the original studies and some correspond to refining the knowledge and experience gained recently from operation of the MERIT test loop. The simulations and system engineering aspects of the target R&D were presented in Section 3.6. Here we cover needed component R&D tasks.

Initially, we must incorporate the existing MERIT syringe pump into a new loop that is more prototypical of the system described in Study 2. Creating such a loop would provide the capability to further study Hg nozzle configurations as well as methods of successfully capturing the jet in a collection pool with minimal splashing. Flow within the collection basin is also an issue—active mixing of the pool fluid may be required to eliminate any regions of locally increased temperature. These tests would be in a no-field condition, that is, they do not require integration with the MERIT solenoid. These studies could be performed at ORNL, or optionally at CERN.

A second set of tests would use both the MERIT syringe pump and solenoid in an integrated test environment to compare jet quality via horizontally- and vertically-oriented camera systems.[11] The tests would be performed without a proton beam, and initially without a magnetic field as well, but ultimately require the magnetic field to provide a basis for direct comparison with MERIT results. If this work is carried out at ORNL, significant infrastructure costs would be incurred to provide the required

[11] This was not possible in the MERIT experiment due to the presence of the proton beam, which required radiation-resistant, fiber-optic-based camera systems.

electrical power to operate the MERIT solenoid; these costs have been included in our estimate.

The use of water-cooled, tungsten-carbide spheres as radiation shielding will require scaled testing to determine optimum ball diameter and distribution, as well as to assess properties such as pressure drop and heat transfer coefficient. Thermal-hydraulic simulations will be required to restrict the range of sphere sizes and packing density considered. The results of these tests will be incorporated into the NF RDR and MC ZDR designs.

Another area needing study is that of nozzle integration. The baseline design of the target system calls for an iron plug at the upstream end of the target solenoid to flatten the magnetic field profile and thus reduce the distortion of the jet as it enters the magnet. The nozzle must be incorporated into this plug. Implementation of this concept can be studied with the MERIT solenoid by augmenting it with an iron plug into which the nozzle is integrated.

Finally, an opportunity exists to collaborate with the ESS/Eurisol project on issues of mercury handling, including possible hardware studies at the Institute of Physics of the University of Latvia. We will develop a well-defined plan and cost estimate for this collaborative work as part of our present R&D effort.

5.7 Related R&D

The main R&D elements presented above are well developed and understood projects for which not only the main goals, but also the needed resources, deliverables, and schedules are well defined. There are other research proposals that promise significant insight into the science and technology of muon accelerators but which have either been proposed only recently or have not yet been carefully evaluated. Several of the most interesting ones are outlined below. Most of them are comparatively inexpensive, as they assume the use or modification of existing facilities and/or test setups. It is expected that the R&D program proposed here will provide support for only one or a few of them; further studies are needed to identify which ones might be worthy of support. Of course, separate support made available from U.S. universities, SBIR companies or international partners might elevate the level of interest in some of these R&D proposals.

5.7.1 *Parametric Ionization Cooling optical channel model*

Parametric Ionization Cooling (PIC) has been proposed to obtain very low emittance muon bunches in the final stages of cooling for a MC [41]. The challenge of having a resonantly excited beam that remains stable is the need to control chromatic, non-linear and space-charge aberrations. While it is not feasible in the near future to do experiments with beams of muons, use of widely available medium energy electron beams seems a very attractive possibility.

Fermilab's A0 Photoinjector provides a good quality electron beam with momentum up to 16 MeV/c. This facility could be employed in the study of PIC magnetic focusing channel elements (of course, without absorbers). In its current configuration, the A0 Photoinjector has two beam lines. One of them, with two "dog-legs" and a transverse electric field cavity, is used for the Emittance Exchange experiment. The second one is straight, with a length of 340.5 cm, and could be used for the PIC test. A magnetic spectrometer would be added to the end of the line. A schematic of the proposed test setup is shown in Fig. 9.

The beam line lattice comprises three normal conducting solenoids, each 60 cm in length, separated by drift spaces of 36 cm. Each drift space would house OTR and BPM diagnostics. A plot of the beta functions along the test beam line is shown in Fig. 10.

Carrying out this work would require additional effort for design of the solenoids and bending magnets, along with M&S for fabricating them. These costs are included in Appendices 3 and 4.

5.7.2 *Intense bunch acceleration test*

In order to investigate acceleration of very intense bunches in an ILC-type acceleration structure, it would be desirable to develop an injector capable of producing electron bunches having 10^{11}–10^{12} particles with an initial rms bunch length of 50–60 cm followed by further compression down to 6–13 mm. Thus, the peak current in the bunch would be 50–500 A, which is a challenge. The 430 MHz linac of the positron source of

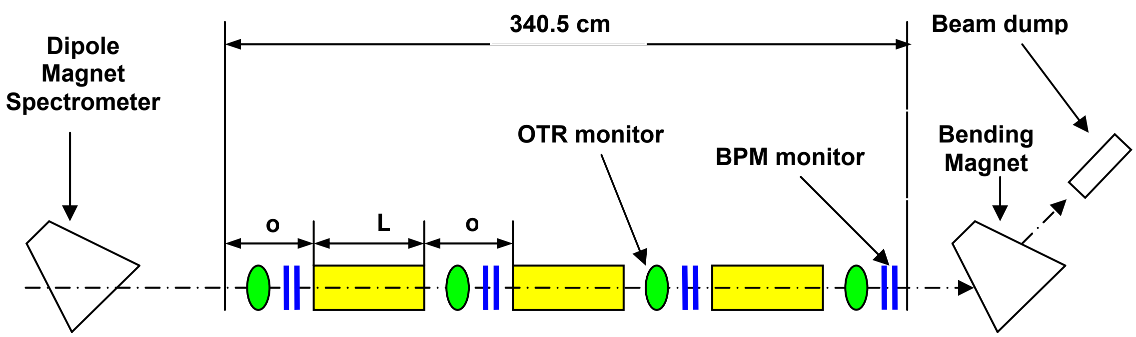

Fig. 9. Setup of the PIC optics study at the A0 Photoinjector.

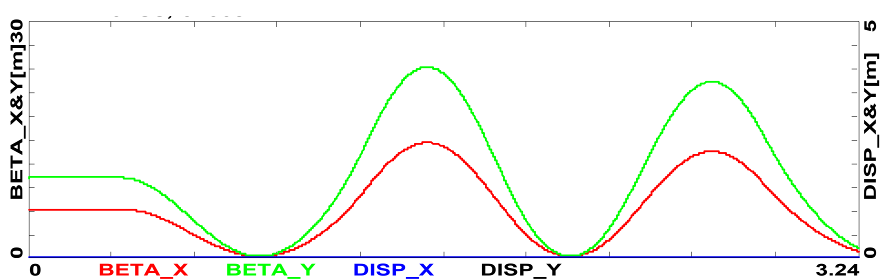

Fig. 10. Beta functions of the beam line for PIC modeling.

the VEPP-4 storage ring provides a train of bunches with an average current of 30 A in a 25 ns pulse, i.e., 9 bunches with a population of 4.4×10^{11}. This is about what is desired. The linac has an output energy of 55 MeV and is operated in the stored energy mode—the cavities are filled by the rf source in 11 μs and a beam with a short pulse is accelerated in the stored rf field. The electron gun unit that contains the grid and lanthanum hexaboride cathode was placed directly before the first acceleration cavity (so-called "internal injection"), and a short DC pulse was used for electron extraction.

It is possible to use the same concept to develop a one-bunch injector with high bunch charge. We wish to use an operating frequency that is not too high in order to avoid strong beam loading and, thus, a large energy spread inside the bunch. The exact frequency choice will be determined by available klystrons. For example, a 3-MW, 325-MHz E3740A Toshiba klystron might be used. The accelerator will comprise the ~4–5 MeV one or two cavity linac, the cathode and grid unit for internal injection, and the focusing system. Along with the klystron station, a pulser is needed to apply the ~3 ns DC pulse necessary for the bunch injection.

5.7.3 *Ionization cooling studies in rings*

The first observations of ionization cooling in a ring were reported more than 40 years ago in experiments [42] with 1 MeV protons. Similar observations in an 11 MeV proton FFAG ring were made recently in Osaka [43]. It is of interest to explore the dynamics of the ionization cooling process with low energy protons, which do not suffer much from nuclear interactions in an absorber and, at the same time, effectively lose energy due to ionization. The experimental program might be carried out either at a newly built 4 m circumference dedicated ring to accommodate 750 keV protons from the FNAL Cockcroft-Walton accelerator or at the Osaka University FFAG ring for dedicated ionization cooling studies. The latter choice would require development of transverse emittance diagnostics, construction of wedge absorbers, and support for visits to Japan.

5.7.4 *High-efficiency high charge acceleration*

The short lifetime of muons necessitates the use of high-gradient accelerating structures in order to reach energies in the TeV range with minimal intensity losses. There are important differences with e^+e^- linear colliders that warrant special attention. We require a large bunch population ($1–2 \times 10^{12}$ for a 0.75+0.75 TeV collider, and even larger for higher energies) in a small number of bunches (just one of either sign in the baseline scheme).

Transient beam-loading effects may present an insurmountable obstacle to using high-gradient rf structures of the ILC type, whereas induction acceleration structures are intrinsically predisposed toward high beam loading. Until now, the accelerating gradient in such structures has been limited to unacceptably low values, but a recent breakthrough with the so-called "dielectric wall accelerator" (DWA) at LLNL [44] makes it possible to achieve gradients as high as 100 MV/m in short pulses (<3 ns). A number of issues remain to be resolved:

- Development of cost- and energy-efficient commutating elements (photoconductive switches, DSRDs)
- Development of methods to control the accelerating pulse shape under varying beam loading
- Simulations and proof-of principle tests
- Design and simulation studies of a high-gradient induction acceleration column
- Analysis of transverse wakes and their effect on transverse emittance growth

It is anticipated that as soon as DWA structures with gradients as high 100 MV/m become available, a short section of DWA could be purchased and set up for beam tests with high-charge electron bunches, either at the Argonne AWA or at Fermilab's A0 Photoinjector facility.

5.7.5 *Development of liquid Li lens technology*

For a long time, Li lenses were considered to be a very attractive technology for the final stages of ionization cooling [45]. A current carrying rod with radius *r* has a surface magnetic field of *B[T]=20 I[MA]/r[cm],* e.g., about 40 T for 1 MA of current in a 10 mm diameter conductor. The field is zero in the center of the rod. In such a field gradient, a 200 MeV/c muon will be strongly focused and will oscillate with an equivalent beta-function of less than 1 cm. Such a low beta allows cooling to very small equilibrium transverse emittances, as needed for a high luminosity MC.

The technology of solid Li lenses is well established. The lenses employed in the Fermilab antiproton production station run for a few million pulses at a current of 0.5 MA in a 10 mm radius conductor. The repetition rate is 0.5 Hz, which is an order of magnitude lower than the minimum required for the MC (5 Hz or above). Heat generation by the current at the required higher rate will melt the lithium. Therefore, a development program for a liquid-lithium lens is needed in order to evaluate its technical feasibility. It is expected that the existing FNAL antiproton source Li lens infrastructure (power supplies, transformers, diagnostics, etc.) will be fully available for test purposes after the end of Tevatron Collider Run II (October, 2010).

6. UNIVERSITY, INTERNATIONAL, AND SBIR COMPANY PARTICIPATION

Accelerator R&D projects provide an excellent training ground for accelerator physics students and post-doctoral research associates. Both the NFMCC and MCTF activities are built around close and productive collaborations between laboratory and university groups. In recent years, the muon accelerator R&D program has provided three Ph.D. projects, all brought successfully to completion on topics ranging from rf studies to beam dynamics. The proposed R&D program for the coming 5 years provides an opportunity for many more thesis topics, and a continued and enhanced opportunity for university group involvement. Based on our experience to date, a university group consisting of one faculty member, one post-doctoral research associate, and one or more graduate students, can make a valuable and valued contribution to the overall R&D program. Although the majority of the resources we are requesting for muon accelerator R&D would be utilized by the national laboratories, the proposed program would also support significant university involvement. The present U.S. university groups that are playing an integral role in the muon accelerator R&D program are Cornell, IIT, University of Mississippi, Princeton, UCLA, and UC-Riverside. Other groups have been more active in the past, but lack resources for active involvement at present. We anticipate that with increased muon accelerator R&D support the university involvement would grow, with about eight groups making significant contributions.

Several Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) companies already very actively contribute to muon accelerator R&D projects. The most notable examples are Muons, Inc., Tech-X Corporation, and Particle Beam Lasers, Inc., all of which have initiated and carried out a number of very important studies on the physics and technologies of the MC and NF. The proposed R&D plan will provide guidance and permit closer coordination between the SBIR/STTR companies and the research at the National Labs and Universities. It is anticipated that the companies will continue to contribute to the R&D on HTS magnets, high pressure gas-filled rf cavity studies, 6-dimensional cooling channel design, prototyping and experiments and in the design and end-to-end simulations of the Muon Collider and Neutrino Factory. The SBIR/STTR companies may also take a leading role in the development of some of the concepts listed in Section 5.6 and contribute to planning and development of various experimental tests.

At present, activities of both the NFMCC and MCTF involve significant international participation. This plan calls for deeper and wider international cooperation. The most important international activities will be the MICE experiment and the Neutrino Factory RDR work. As indicated in Section 5.6, the 5-year plan seeks additional international participation in development of the advanced muon accelerator physics and technology concepts.

7. SUMMARY

By 2012 we expect that new physics results from the LHC and from the next generation of neutrino experiments (Double Chooz, Daya Bay, T2K, and Nova) will be available. These will provide the worldwide HEP community with the knowledge it needs to identify which types of facilities are best suited to fully exploit the exciting new physics opportunities that will undoubtedly arise. In particular, we expect that the physics cases for both a multi-TeV lepton collider and a Neutrino Factory will be more fully understood at this time.

The R&D program that we have outlined in this proposal will provide the HEP community with detailed information on future facilities based on intense beams of muons—the Muon Collider and the Neutrino Factory. We believe that these facilities, which could be considered separately or as part of a staged approach to a world-class scientific program, offer the promise of extraordinary physics capabilities. The Muon Collider presents a powerful option to explore the energy frontier and the Neutrino Factory gives the opportunity to perform the most sensitive neutrino oscillation experiments possible, while also opening expanded avenues for study of new physics in the neutrino sector. The synergy between the two facilities presents the opportunity for an extremely broad physics program and a unique pathway in accelerator facilities.

Facilities based on short-lived muons present many challenges, both for the accelerator builder and for the detector builder. It is addressing these challenges in a timely way that motivates this proposal, which covers all three aspects of muon facilities that are of importance to the HEP community—the physics reach, the accelerator design, and the detector design. Specifically, the program presented here, if funded at the requested level, would deliver a ZDR for a Muon Collider and (with our international partners) an RDR for the Neutrino Factory by the end of 2012.

Our work will give clear answers to the questions of expected capabilities and performance of these muon-based facilities, and will provide defensible estimates for their cost. This information, along with the physics insights gained from the next-generation neutrino and LHC experiments, will allow the HEP community to make well-informed decisions regarding the optimal choice of new facilities. We believe that this work is an absolutely critical part of any broad strategic program in accelerator R&D and, as the P5 panel has recently indicated, is essential for the long-term health of high-energy physics.

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APPENDIX 1: PRESENT FUNDING LEVEL (M.Z. + V. S.)
M&S + SWF

APPENDIX 2: COOLING CHANNEL DECISION TREE (A.J.)

APPENDIX 3: M&S REQUEST

APPENDIX 4: SWF REQUEST

APPENDIX 5: FUNDING PROFILE